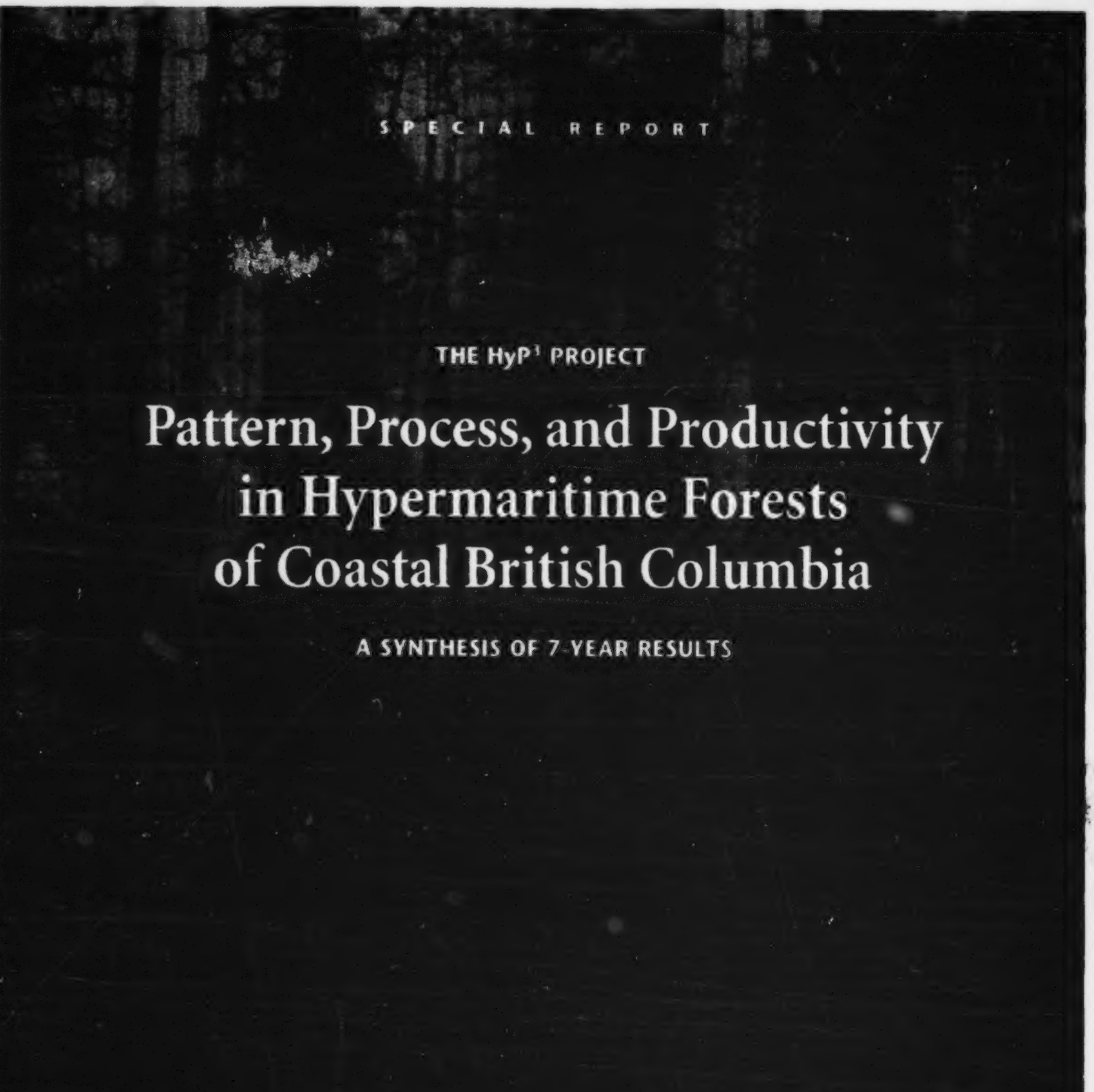

SPECIAL REPORT

THE HyP³ PROJECT

Pattern, Process, and Productivity in Hypermaritime Forests of Coastal British Columbia

A SYNTHESIS OF 7-YEAR RESULTS

2005

BRITISH COLUMBIA

The HyP^3 Project

Pattern, Process, and Productivity in Hypermaritime Forests of Coastal British Columbia

A Synthesis of 7-Year Results

Compiled & Edited by:

Allen Banner, Phil LePage, Jen Moran, & Adrian de Groot

BRITISH
COLUMBIA

Ministry of Forests
Forest Science Program

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EXECUTIVE SUMMARY

The HyP^3 Project (pronounced "hip cubed") was initiated in 1997 to provide an integrated research approach to the study of pattern, process, and productivity in the hypermaritime forests of north coastal British Columbia. The project has four main goals:

- Document the ecology of the blanket bog–upland forest complex of north coastal British Columbia.
- Assess the feasibility of managing poor- and low-productivity cedar–hemlock forests, which dominate the outer coastal landscape, for timber and fibre production.
- Define the extent of these sites and identify the potentially operable portion.
- Develop ecologically based management guidelines for these forests.

The need for this research was made clear in the 1995 timber supply review for the North Coast Timber Supply Area. This report stated that the Chief Forester required better scientific information before he would consider expanding the operable land base into lower-productivity cedar-dominated (western redcedar [*Thuja plicata*] and yellow-cedar [*Chamaecyparis nootkatensis*]) forests. Research was required that would address basic ecosystem function (e.g., watershed and soil hydrology, plant and soil ecology, succession and stand dynamics) and provide practical management guidelines for these forest types.

This report presents a synthesis of the HyP^3 Project's 7-year results. It provides an overview of the project to date and summarizes initial results for each of the project components—hydrology and biogeochemistry, ecosystem processes, classification and inventory, and operational trials. The report concludes with a chapter on management interpretations.

Chapters 1 and 2 provide the background to the research, including a review of previous studies. These chapters also present descriptions of the north coast landscape and the specific study areas, stand types, and ecosystems targeted for the research. The geographic scope of the project encompasses the Coastal Western Hemlock zone, Very Wet Hypermaritime subzone, Central variant (CWHvh2) within the North Coast and North Island–Central Coast forest districts of the Coast Forest Region. The blanket bog–upland forest complex of the CWHvh2 contains approximately 235 000 ha of lower-productivity cedar-dominated stands that straddle the defined operability thresholds for height class, merchantable volume, and site limitations. As market values for redcedar and yellow-cedar improve, pressure increases to alter the operability thresholds. This has already begun to occur on the north coast, and because this research is now under way, preliminary management guidelines can be in place before operability pressures increase dramatically. From an ecological perspective, the outer coast of British Columbia is a fascinating landscape and a major thrust of the research is simply to gain a better ecological understanding of these hypermaritime forests and wetlands.

Chapter 3 describes studies of site and watershed hydrology and biogeochemistry. Water plays a pivotal role in shaping ecosystem function on the outer coast, and thus hydrological studies are an important part of the HyP^3 Project. To produce water budgets for small watersheds and predict the potential effects of timber harvesting on these water budgets, watershed-level studies included monitoring of precipitation, interception, throughfall, and streamflow. Site-level studies examined water table dynamics, hydrological linkages between sites, and natural soil drainage mechanisms such as soil pipes. Soil water chemistry across the spectrum of forest and bog ecosystems in the CWHvh2 is also characterized.

Hypermaritime watersheds of the CWHvh2 have a relatively low water storage capacity. The shallow, dominantly organic, soils typical of these watersheds have high water retention capacity, and are frequently saturated in this wet climate. The small amount of available water storage capacity in these soils means that significant runoff is generated from relatively small storms. Compared with other locations, rainfall events in the CWHvh2 produce a larger hydrological response.

The decrease in canopy interception after harvesting increases the amount of water received on the ground. At the HyP^3 study sites, the canopy intercepted 20–25% of the average annual rainfall. If these areas are clear-cut, the amount of water requiring removal by existing hydrological processes can be expected to increase. The possible hydrological consequences of these increased water inputs include faster development and increased volume of peak flows, higher water tables, and increased erosion resulting from overland flow.

Organic soils (especially on disturbed sites) have high water retention and low cohesion qualities, and therefore the possibility of increased erosion must be considered. The relatively gentle slopes on which these low-productivity forests occur, however, will result in lower surface water runoff velocities, and thus lower off-site sediment transport than on steeper hillslopes. Using the current watershed assessment procedures for road building and bridge engineering, the management of additional water to a drainage system is possible. By knowing the harvested area and the watershed's discharge characteristics, the potential increase in peak flows can be identified and accounted for in management plans.

Hydrological dynamics differ among forest types. Our study indicates that the cedar-dominated upland scrub forests (i.e., the target stands of the HyP^3 Project; CWHvh2/01 sites) will likely have an on-site hydrological response to harvesting that is intermediate between the wetter swamp forests and the more productive upland forests. Water tables are likely to rise slightly depending on specific site and soil characteristics. Compared with the upland scrub forests, the true swamp forests are quite restricted in distribution on the coast. The swamps are more sensitive to harvesting-induced hydrological changes than upland forests; they should not be harvested because of their importance in receiving water and regulating streamflow within a watershed, and their greater potential for rising water tables. Where scrub forests occur on flat or very gently sloping sites, a rise in the water table following timber harvesting is expected and could have negative ecological implications. Smaller rainfall events would saturate these forest soils because of the reduced interception and transpiration following canopy removal. This may hamper regeneration and promote paludification, with the invasion of sphagnum mosses and other wetland plants. As forests regenerate, canopy interception and transpiration begin to increase again, but the time required for hydrological recovery is still uncertain in this hypermaritime environment. Long-term monitoring of current and future operational trials will help answer this question.

High water tables and high levels of acidity limit nutrient availability by restricting rooting depth and maintaining anaerobic soil conditions that prevent the oxidization of nutrients to available forms. Our study shows that the highest ion concentrations in soil water occur in well-drained (productive forest) vegetation types, which have deeper water tables and thicker aerobic zones.

Naturally formed soil pipes play an important role in draining forests in the hypermaritime north coast. Soil pipes transport stormflow rapidly and efficiently; however, if harvesting damages these pipes, they could become "short-circuited," decreasing their capacity to route stormflow through the landscape.

After harvesting, dissolved organic carbon (DOC) levels could increase along with the greater water inputs to a site. If DOC increases a large amount after harvesting, water quality can be affected. Some evidence from southeast Alaska suggests, however, that peatland streams are better adapted to handle an increase of DOC after harvest than the non-peatland systems. The non-peatland systems are thus more susceptible to changes in stream biology resulting from increased DOC inputs after harvest. Future operational trials in lower-productivity western redcedar–hemlock forests should include a soil water monitoring program. Such a program could better quantify changes in water table levels and DOC and ion concentrations in soil and stream waters associated with harvesting.

Chapter 4 describes studies of ecosystem processes, including disturbance and ecological succession, vegetation dynamics, production and decomposition, nutrient cycling, and other aspects of soil ecology. Organic matter dynamics, including rates of forest humus and peat accumulation, is an important ecosystem process on the outer coast, where organic soil layers play a vital role in determining successional trends and site productivity.

The many peatlands that characterize the coastal landscape preserve a record of past conditions in their pollen and macrofossil profiles. These profiles provide the data against which we can compare current conditions, and predict future hydrological and related ecosystem responses to natural and human-influenced disturbances. Core sampling at several sites was conducted to reconstruct historical vegetation patterns and rates of peat accumulation. Production and decomposition rates within present-day vascular plant and moss communities were measured to estimate current rates of accumulation. These studies included detailed measurements of annual sphagnum moss productivity and colonization on both disturbed and undisturbed sites.

HyP^3 research also included studies of bedrock, soil property, and site productivity relationships in both old-growth and second-growth stands across the spectrum of site series, from bog woodland and scrub forest to productive upland forest.

From these ecosystem process studies, a simple model of ecosystem development in the CWHvh2 has emerged. In this model, three main factors operate in combination to drive ecosystem development and productivity in this hypermaritime environment:

1. bedrock geology
2. soil drainage
3. disturbance history

Although these same factors influence ecosystem development to some degree in most other terrestrial environments, their influence is especially dramatic in the CWHvh2.

The scarcity of glacial till in this coastal environment highlights the importance of bedrock geology. Most soils develop directly from the weathering of bedrock or colluvial material. This contrasts with many other areas where a mantle of glacial till of mixed lithology masks the influence of bedrock. In addition, sharp contrasts in bedrock type occur on the outer coast, from the hard, slowly weathering granodiorites with relatively low amounts of available nutrient elements, to the much softer, easily weathered metamorphic rocks and limestone with more nutrient-rich lithologies. These different bedrock types manifest themselves in dramatic differences in plant communities and forest productivity.

Excess soil water is the rule in this hypermaritime environment, and subtle variations in slope or internal soil drainage result in significant differences in forest productivity. In contrast to the majority of other subzones in the province (where moisture deficits are common), the most freely drained sites in the CWHvh2 are the most productive sites for trees. Even these "drier" sites are fresh to moist in absolute terms, and as long as soil water is moving, rather than stagnant, tree productivity will remain moderate to high.

The tendency for organic matter to accumulate on sites that have not been disturbed by landslides, windthrow, or fluvial disturbances for hundreds (or thousands) of years is also dramatic in the CWHvh2. As soil organic matter accumulates, soils become wetter and tree roots become more confined to surface organic horizons. Although the nutrient capital in these organic horizons is considerable, nutrient availability is relatively low because of the wet, acidic conditions and low rates of nitrogen mineralization. Better-drained sites, which often have a history of natural disturbance, especially where soil organic and mineral horizons are mixed, exhibit higher forest productivity.

Although models are inherently simplistic, ecosystem development and forest productivity on the majority of sites on the outer coast are largely driven by bedrock geology, soil drainage, and disturbance history working in combination. The model presented in Chapter 4 can also be used to guide forest management investments and activities, and to help define and understand the limits of operability in the CWHvh2. For example, marginally productive sites occurring on metamorphic rock will exhibit higher second-growth productivity following harvesting and site treatments compared with a similar site on granodiorites.

Two variations of the model are presented—one emphasizing forest productivity, and one emphasizing biomass allocation. As indicated by the soil ecology, moss productivity, and succession studies, a switch in biomass allocation from trees to mosses (and other understorey vegetation) occurs as sites paludify and tree productivity declines. Bogs and bog forests are often referred to as "low productivity." They are, however, highly productive if one considers the annual rates of total biomass accumulation in these ecosystems.

Chapter 5 presents the classification and inventory component of the HyP³ Project, which serves as the link between the hydrology and ecosystem process components and the application of results across the north coast. The project has used the Biogeoclimatic Ecosystem Classification (BEC) system as the framework to make ecologically based forest management recommendations. BEC uses the site series to classify forests for management purposes. Ecosystem classification is invaluable for choosing appropriate sites for in-depth studies, and for extrapolating the results to other similar sites on the north coast.

We conducted sampling to collect baseline information on tree growth and site productivity throughout the range of forested site series in the CWHvh2. These data show that estimates of site productivity from old-growth stands significantly underestimate second-growth site potential. On CWHvh2/01 (upland scrub forest) sites, for example, western redcedar site index at breast height age 50 years, averages 18 m in second-growth stands, but estimates of 10 m or less are derived from old-growth stands. Past timber supply analyses have used the old-growth productivity estimates from the forest cover inventory database to model the growth and yield of regenerating stands. This suggests that potential yields of second-growth CWHvh2/01 sites, as well as other currently operable sites, are underestimated. HyP³ results clearly indicate that second-growth productivity of these scrub forests is high enough to consider them as potentially operable, subject to the assessment of other site limitations.

At each of the HyP^3 study sites, timber cruising was carried out to quantify stand structure, species composition, and gross and merchantable volume. Several forest mensuration attributes are summarized from these data for each of the CWHvh2 site series studied. Rare, or otherwise threatened or imperiled ecosystems of the CWHvh2 are also reviewed to examine the potential effects of expanding forestry operations into the lower productivity forest types.

A predictive ecosystem mapping (PEM) model was developed for the outer coast. The resulting maps identify the site series most likely associated with each forest cover polygon. These maps help to establish the extent and location of potentially operable low-productivity cedar–hemlock forest types. Site series productivity data can also be combined with these maps to aid in growth and yield analysis.

Chapter 6 describes the HyP^3 operational research trials at Port Simpson and Oona River. The trial near Port Simpson, north of Prince Rupert, was established in 1990 to examine second-growth productivity in the poor cedar–hemlock forest type. Initially funded by South Moresby Forest Replacement Account (SMFRA) research funds, this study was taken over by the HyP^3 Project in 1999. The Port Simpson trial focused on the effect of mounding on the survival and growth of planted seedlings and on some of the ecological impacts of site treatments. The Oona River operational trial is located on Porcher Island, south of Prince Rupert. This is a more expansive trial and was established in 1998 to test some of the management ideas gained from both the Port Simpson trial and the multitude of research studies undertaken on CWHvh2/01 sites around Prince Rupert. The Oona River trial examines several ecological and operational aspects of forest management activities on the low-productivity cedar–hemlock sites.

Results from the Port Simpson trial suggest that site preparation, including soil mixing and mounding, improves regeneration success and tree growth and nutrition on poor cedar–hemlock sites. Care must be taken, however, to avoid creating conditions (e.g., pools beside mounds) that facilitate sphagnum moss growth and paludification. Monitoring of planted and natural regeneration, as well as moss and vascular plant succession, at this site will continue into the future. Block layout, harvesting, site treatments, planting, and initial regeneration surveys are complete at the Oona River trial. Planted western redcedar survival and growth results are very encouraging and reinforce the belief that CWHvh2/01 sites have significant forest management potential. Long-term monitoring of this trial will take place to ensure that early trends continue and management interpretations remain current and realistic.

Chapter 7 presents management interpretations resulting from the first 7 years of HyP^3 research and operational trials. The HyP^3 Project focuses primarily on the ecological and operational feasibility of sustainable forest management practices on the CWHvh2/01 sites. The economics of the operations were not examined because the value of western redcedar is quite variable, and subtle changes will significantly affect the economic viability of managing these sites.

Low-productivity sites in the CWHvh2 belong primarily to the Western redcedar – Western hemlock – Salal site series (CWHvh2 /01). These sites typically have between 200 and 300 m^3/ha merchantable volume. The vast majority of these sites are currently outside the operable land base. At the upper end of the productivity spectrum for these site series, soil and vegetation conditions become transitional to the Western hemlock – Sitka spruce – Lanky moss site series (CWHvh2/04), which is currently included in the operable land base (merchantable volumes typically greater than 400 m^3/ha). At the lower extremes of productivity for the CWHvh2/01 site series, conditions are transitional to the Western redcedar – Yellow-cedar – Goldthread site series (CWHvh2/11), in which merchantable wood volumes (typically less than 150 m^3/ha) are well below current and projected operability limits.

Historical ecosystem classification data were used to develop better descriptions of these hypermaritime ecosystems, especially for the lower-productivity forest types of interest in this study. By combining this information with HyP^3 Project results, we have defined a set of criteria to identify those CWHvh2/01 sites with the greatest potential for sustainable forest management. These criteria include: depth and nature of mineral and organic soil horizons, bedrock geology, overstorey and understorey composition, and stand volume. Other information, such as location and access, should be used in combination with these site factors to determine overall operability on a site-specific basis. We will further refine these operability criteria as we gain more experience in these forest types.

Specific recommendations are provided on block layout, harvesting methods, site preparation treatments, and planting on CWHvh2/01 sites. Chapter 7 concludes with a summary of the future research required to further develop and test our current management recommendations for these hypermaritime ecosystems.

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CONTENTS

Contributing Authors iii

Executive Summary iv

Acknowledgements x

- 1 **Introduction** 1
  - 1.1 The Issue 1
  - 1.2 HyP3 Research Approach 4
  - 1.3 Previous Studies: Historical Perspective 6
- 2 **Location and Environmental Setting** 10
  - 2.1 Location, Physiography, and Geology 10
  - 2.2 Climate 11
  - 2.3 Vegetation, Soils, and Ecosystems 12
  - 2.4 Natural Disturbance Regimes 15
  - 2.5 Adjacent Biogeoclimatic Units 16
  - 2.6 HyP^3 Study Sites 16
- 3 **Hydrology and Biogeochemistry** 19
  - 3.1 Introduction 19
  - 3.2 Watershed Hydrology 19
  - 3.3 Soil Hydrology and Biogeochemistry 29
  - 3.4 Discussion and Summary 41
- 4 **Ecosystem Processes** 47
  - 4.1 Introduction 47
  - 4.2 Succession and Disturbance 47
  - 4.3 Paludification and Vegetation Dynamics 51
  - 4.4 Vegetation Types and their Dynamics: Discussion 66
  - 4.5 Soil Ecology 68
  - 4.6 Model of Ecosystem Development and Productivity in the CWHvh2 80
- 5 **Classification and Inventory** 82
  - 5.1 Introduction and Approach 82
  - 5.2 Site Series Descriptions 82
  - 5.3 Site Productivity 86
  - 5.4 Forest Mensuration 89
  - 5.5 Biodiversity Considerations 94
  - 5.6 Predictive Ecosystem Mapping 101
- 6 **Operational Research Trials** 105
  - 6.1 Introduction 105
  - 6.2 Port Simpson 105
  - 6.3 Oona River 109
- 7 **Management Interpretations** 118
  - 7.1 Identification of Potentially Operable Sites 118
  - 7.2 Silvicultural Systems 118
  - 7.3 Future Research Direction 123

Glossary 127
References 130

APPENDIX

1 HyP^3 Project-related Extension Notes 126

TABLES

2.1 Climatic data for the CWHvh2 and some adjacent subzones 12
3.1 Total monthly rainfall by site and elevation, correlated to the North Pacific Cannery reference site at Port Edward 23
3.2 Percentage of rainfall by wind direction 25
3.3 Annual rainfall, throughfall, stemflow, and interception at the Smith Island and Diana Lake sites 25
3.4 Maximum and minimum monthly interception as a percentage of rainfall at the Smith Island and Diana Lake sites 25
3.5 Rainfall interception sorted by canopy condition, event intensity, and event length 27
3.6 Production of stemflow by tree size class 28
3.7 Water balance for the Smith Island and Diana Lake watersheds, 1998–2001 28
3.8 Average depth to water table, pH, and dissolved organic carbon of groundwater from mineral and organic soil horizons by site series 31
3.9 Characteristics of the S01 and K-pipe basins 34
3.10 Mean ionic composition of groundwater by site series at Diana Lake, 1997–1998 40
3.11 Mean ionic composition of groundwater in the organic and mineral subsoil horizons at Diana Lake, 1997–1998 40
3.12 Mean seasonal ionic composition of groundwater at Diana Lake, 1997–1998 40
4.1 Growth and production of sphagnum and other mosses and their correlation with climatic parameters 52
4.2 Vegetation classified at the Diana Lake study site by two-way indicator species analysis 55
4.3 Vegetation classified at the Port Simpson study site by two-way indicator species analysis 59
4.4 Estimated total net primary production for the five representative micro-communities in the open bog at the Diana Lake study site 65
4.5 Mass loss of *Sphagnum fuscum* litter from litter bags incubated at 10 cm below ground surface for 1 year 65
4.6 Total chemical concentrations for bedrock types 69
4.7 Mean organic and mineral soil depths for CWHvh2 site series on the north and central coast of British Columbia 70
4.8 Mean organic and mineral soil depths for CWHvh2/01 and CWHvh2/04 site series by bedrock type on the north and central coast of British Columbia 70
4.9 Average chemical properties of mineral soils, well-drained sites only 70
4.10 Foliar nutrient concentrations for western hemlock, Sitka spruce, and western redcedar on productive sites of north coast British Columbia 78

4.11 Average height increment for each tree species by soil moisture regime and bedrock type 79
5.1 Old-growth and second-growth productivity data for the CWHvh2, north coast of British Columbia 88
5.2 Summary of average stand characteristics for the CWHvh2/11, /01, and /04 site series at the Diana Lake, Oona River, and Smith Island study areas 89
5.3 Tree heights used for height class designations 93
5.4 Summary of average stand characteristics for the CWHvh2/11 site series at the three study sites 93
5.5 Summary of average stand characteristics for the CWHvh2/01 site series at the three study sites 93
5.6 Summary of stand characteristics for the CWHvh2/04 site series at the three study sites 94
5.7 Red- and blue-listed ecosystems of the hypermaritime mainland coast of British Columbia 95
5.8 A comparison of foliicolous lichens and bryophytes from Porcher Island and those reported by Vitt et al. (1973) from other coastal localities in British Columbia 101
6.1 Substrate descriptions at Port Simpson mounding trial 106
6.2 Average percent survival and height of planted western redcedar seedlings at Oona River 115
6.3 Cruised and call-graded merchantable timber volumes by log grade and species from the Oona River operational research trial 116
7.1 Site identification criteria for determining operability of Western redcedar – Western hemlock – Salal (01) sites CWHvh2 119

FIGURES

1.1 North Coast Timber Supply Area, British Columbia, Canada 2
1.2 Harvested sites on highly productive steep slopes of the CWHvh2 subzone 2
1.3 Distribution of the CWHvh2 within the North Coast Forest District 3
1.4 Landslide associated with mid-1980s road-building activities, coastal British Columbia 4
2.1 Generalized bedrock geology, central and north coast of British Columbia 11
2.2 Upland productive forest type, CWHvh2/06 13
2.3 Upland scrub forest type, CWHvh2/01 13
2.4 Bog forest type, CWHvh2/11 13
2.5 Bog woodland forest type, CWHvh2/12 13
2.6 Blanket bog, CWHvh2/32 13
2.7 Edatopic grid depicting forested site series of the CWHvh2 subzone 14
2.8 Open bog development on 2 m of accumulated peat near Prince Rupert 15
2.9 Location of HyP^3 intensive study sites and operational trial sites on the north coast of British Columbia 17
3.1 Trough system used to collect rain "throughfall" data at the Diana Lake study site 20
3.2 Stemflow collection system on a redcedar tree at the Smith Island study site 21

3.3 V-notch weir for measuring discharge on a bog stream at the Diana Lake study site 21
3.4 Hydrological response and lag time for small and large rainfall events in the Smith and Diana watersheds 22
3.5 Frequency distribution of rainfall events greater than 1 mm at the Diana Lake study site 23
3.6 Percent of total rainfall by event size category at the Diana Lake study site 24
3.7 Interception as a percentage of rainfall, by rainfall event, at the Diana Lake and Smith Island sites 26
3.8 Conceptual model of discontinuous soil pipes forming linkages with localized dynamic contributing area 29
3.9 Model of groundwater flowpaths in zonal forests and open bogs in the Smith Island watershed 32
3.10 Examples of soil pipes 33
3.11 Comparison of typical storm hydrograph response between the K-pipe and S01 basins 36
3.12 Selected storm recession graphs for the K-pipe and S01 basins during the 2000 field season 37
3.13 Relationship between the S01 basin and K-pipe basin dynamic contributing areas and 10-day antecedent rain 37
3.14 Hydrological parameters measured in a bog at the Diana Lake study site 38
3.15 Dissolved organic carbon concentrations, rainfall, and stream discharge, Smith Island watershed 41
4.1 Historical climatic conditions on the north coast relative to present conditions 49
4.2 Canonical correspondence analysis of Diana Lake study plots 58
4.3 Depressions created by mounding at Port Simpson filled in with sphagnum moss after 6 years 60
4.4 Growth patterns of *Pleurozium schreberi* in relation to climatic parameters for eight consecutive sampling intervals from June 1999 to July 2000 62
4.5 Growth patterns of four *Sphagnum* species in relation to climatic parameters for eight consecutive sampling intervals 63
4.6 Change in cover of *Sphagnum girgensohnii* between 1998 and 1999 at one of the three Port Simpson sites 64
4.7 Four common bedrock types found on the north and central coast of British Columbia 68
4.8 Comparisons of microbial respiration rates and chemical properties 72
4.9 Comparisons of microbial respiration rates and moisture content 73
4.10 Changes in C:N and C:P ratios across CWHvh2 site series in old-growth and second-growth stands 73
4.11 Western hemlock nutrient concentrations for current-year needles and 1-year-old needles across height increment 75
4.12 Sitka spruce foliar nutrient concentrations for current-year needles and 1-year-old needles across height increment 76
4.13 Western redcedar foliar nutrient concentrations for current-year needles and older needles across height increment 77
4.14 Simplified model of ecosystem development and forest productivity in the CWHvh2 80

5.1 Zonal forest (CWHvh2/01), Oona River 83
5.2 Bog forest (CWHvh2/11), Diana Lake 83
5.3 Bog woodland (CWHvh2/12), Diana Lake 84
5.4 Open bog (CWHvh2/32), Diana Lake 84
5.5 Productive upland forest (CWHvh2/06), Port Edward 85
5.6 Productive spruce stand on a CWHvh2/08 site, Barnard Creek, Princess Royal Island 85
5.7 Swamp forest (CWHvh2/13), Diana Lake 86
5.8 Dry, windswept rock outcrop (CWHvh2/02), McCauley Island 86
5.9 Second-growth CWHvh2 stand used for site index sampling, Khyex River 87
5.10 Net merchantable volume per hectare by site series and species at the Diana Lake, Oona River, and Smith Island study sites 90
5.11 Stems per hectare by site series and species at the Diana Lake, Oona River, and Smith Island study sites 90
5.12 Basal area and stems per hectare in diameter classes at the Diana Lake, Oona River, and Smith Island study sites by site series 91
5.13 Stems per hectare in height classes by site series at all sites and by species at the Diana Lake, Oona River, and Smith Island study sites 92
5.14 Productive yellow-cedar stand on Mount Genevieve, Haida Gwaii/Queen Charlotte Islands 96
5.15 Productive Sitka spruce–western redcedar forest on limestone bedrock, Hamner Island 97
5.16 Kerouard Islands, south of Kunghit Island, Haida Gwaii/Queen Charlotte Islands 98
5.17 Tidal estuary, Kwatna Inlet, east of Burke Channel 98
5.18 Sandy beach on the west side of Calvert Island 99
5.19 *Carex sitchensis* fen near Prudhomme Lake, Prince Rupert 100
5.20 The predictive ecosystem mapping procedure 102
5.21 The EcoGen predictive ecosystem mapping approach 103
6.1 Port Simpson mounding trials 106
6.2 Mean height and mean caliper of western redcedar, western hemlock, and shore pine 5 years after planting on mounded and unmounded plots at the Port Simpson study site 107
6.3 Root and shoot biomass of western redcedar, western hemlock, and shore pine 6 years after planting on mounded and unmounded plots at the Port Simpson study site 107
6.4 Rooting characteristics of western redcedar, western hemlock, and shore pine 6 years after planting on mounded and unmounded plots at the Port Simpson study site 107
6.5 Root development of western redcedar growing on unmounded and mounded plots 6 years after planting at the Port Simpson study site 108
6.6 Nitrogen content of pine needles from trees growing on five substrate types at the Port Simpson study site 108
6.7 Macronutrient content of pine needles from trees growing on five substrate types at the Port Simpson study site 109
6.8 Ecosystem map of Oona River study site 110
6.9 Block 1 at the Oona River study site 111

6.10 Excavator "hoe-chucking" logs to main skid trail at the Oona River study site 111
6.11 FMC tracked skidder moving logs to the landing at the Oona River study site 112
6.12 Excavator raking and piling slash in block 1 at the Oona River study site 112
6.13 Mixed mineral and organic mound on a CWHvh2/01 site at the Oona River study site 112
6.14 Seedling protectors tested at the Oona River study site 113
6.15 Western redcedar sample tree marked for stem-analysis cutting 114
6.16 Aerial view of block 1 at Oona River showing the irregular ecosystem-based boundaries and the individual and patch leave trees 115
6.17 Some redcedar siding and dimensional lumber produced at the Group Mills operation at Oona River 117

1 INTRODUCTION

The HyP^3 Project (pronounced "hip cubed") provides an integrated research approach to the study of pattern, process, and productivity in the hypermaritime forests of north coastal British Columbia. Initiated in the North Coast Forest District in 1997, this project aims to develop ecologically based guidelines for the management of cedar-dominated forests, most of which are outside the current operable land base. Lower-productivity cedar–hemlock forests that contain significant amounts of timber, including high-value western redcedar[2] (*Thuja plicata*) and yellow-cedar (*Chamaecyparis nootkatensis*), dominate much of the outer coastal landscape; however, considerable uncertainty surrounds the feasibility and sustainability of harvesting these wet, slow-growing forests.

HyP^3 researchers are using basic studies of ecosystem structure and function, as well as operational trials, to address the following project goals:

- Document the ecology of the blanket bog–upland forest complex of north coastal British Columbia.
- Assess the feasibility of managing poor- and low-productivity cedar–hemlock forests for timber and fibre production.
- Define the extent of these sites and identify the potentially operable portion.
- Develop ecologically based management guidelines for these forests.

This report presents a synthesis of the HyP^3 Project's 7-year results. It provides an overview of the project to date and summarizes initial results for each of the project components—hydrology and biogeochemistry, ecosystem processes, classification and inventory, and operational trials. The report concludes with a chapter on management interpretations. A glossary is also included to define the technical terms used in the text.[3]

1.1 The Issue

The North Coast Timber Supply Area (TSA), within the Coast Forest Region (formerly within the Prince Rupert Forest Region), encompasses 1.95 million ha along the British Columbia coast, extending from Princess Royal Island to southeast Alaska (Figure 1.1). Although 39% (758 788 ha) of the TSA is considered productive forest land, only 6% (119 130 ha) is currently included within the operable (timber harvesting) land base because of limitations associated with environmental concerns, accessibility, and timber size and quality (British Columbia Ministry of Forests 1999).[4]

The effects of hand-logging and A-frame operations, which began at the turn of the 20th century, and the larger industrial operations of today, are readily apparent along the north coast. Harvesting was restricted primarily to the highly productive steep slopes (often adjacent to tidewater) and alluvial valley bottoms (Figure 1.2). These locations yielded the highest volumes per hectare and the greatest return on investment for the relatively costly coastal timber harvesting operations. Harvesting of some species, such as Sitka spruce (*Picea sitchensis*) and amabilis fir (*Abies amabilis*), was disproportionately

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[2] Nomenclature for scientific and common names of vascular and non-vascular plants follows Meidinger et al. (2004).

[3] Technical terms included in the glossary appear in **boldface** at first mention.

[4] The boundary of the North Coast TSA was recently modified and thus the breakdown of the land base provided here has been altered slightly. The area of the TSA currently totals 1.88 million ha.

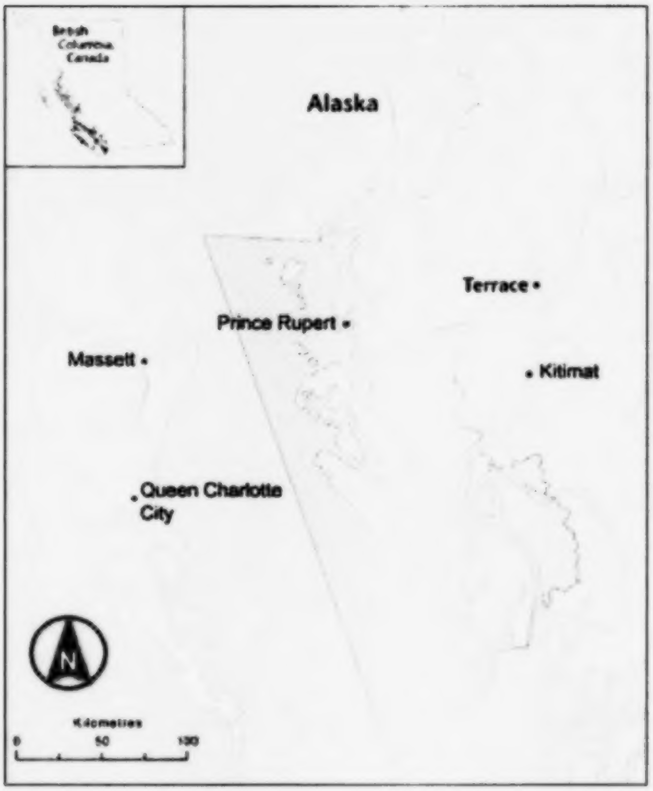

FIGURE 1.1 *North Coast Timber Supply Area, British Columbia, Canada.*

FIGURE 1.2 *Harvested sites on highly productive steep slopes of the CWHvh2 subzone.*

high compared with their percentage of the standing volume. Very little harvesting has occurred in the lower productivity height class 2 and 3 (< 30 m tall) cedar–hemlock stands typical of the gentler north coast terrain. These stands make up 12% of the TSA (roughly 235 000 ha), and contain significant quantities of both western redcedar and yellow-cedar. These two species often grow together with low-quality western hemlock (*Tsuga heterophylla*) and mountain hemlock (*T. mertensiana*), and lesser amounts of shore pine (*Pinus contorta* var. *contorta*). Most of these stands are currently excluded from the operable land base because of their low volume (as determined by inventory height class). As the market value of western redcedar and yellow-cedar increases, so does the attractiveness of these stands for harvesting.

The current allowable annual cut (AAC) for the North Coast Forest District is 573 624 m³.[5] This cut is projected to decline in about 20 years (the so-called "falldown" effect) as we shift from cutting old-growth forests to lower-volume second growth. A long-term harvest rate of 361 000 m³ is predicted by the year 2060 (Pedersen 2001). Harvesting in areas that are now considered inoperable may offset reductions in the AAC, or reduce harvesting pressure in the existing operable land base. Before this potential expansion of the operable area can occur, however, concerns about sustainability must be addressed and satisfactorily resolved. In his 2001 AAC determination, the Chief Forester stated,

> *If and when research results indicate the potential to manage some of the excluded stands for timber production from a biological, silvicultural regime and economic viewpoint . . . then it may be appropriate to consider some level of contribution from these stands in a future timber supply review* (Pedersen 2001).

---

[5] The AAC has recently been reduced to 546 624 m³.

Thus, before any harvesting occurs, researchers must assess whether these stands can be managed sustainably (i.e., in terms of their regenerative capacity and site productivity, and the possible effects on biodiversity and other non-timber resources and values). Although expanding the operable land base could theoretically permit an increase in the AAC (by up to 120 000 m³), the Chief Forester suggested that any expansion should be used to extend existing harvest levels further into the future, therefore maintaining a higher long-term harvest level.

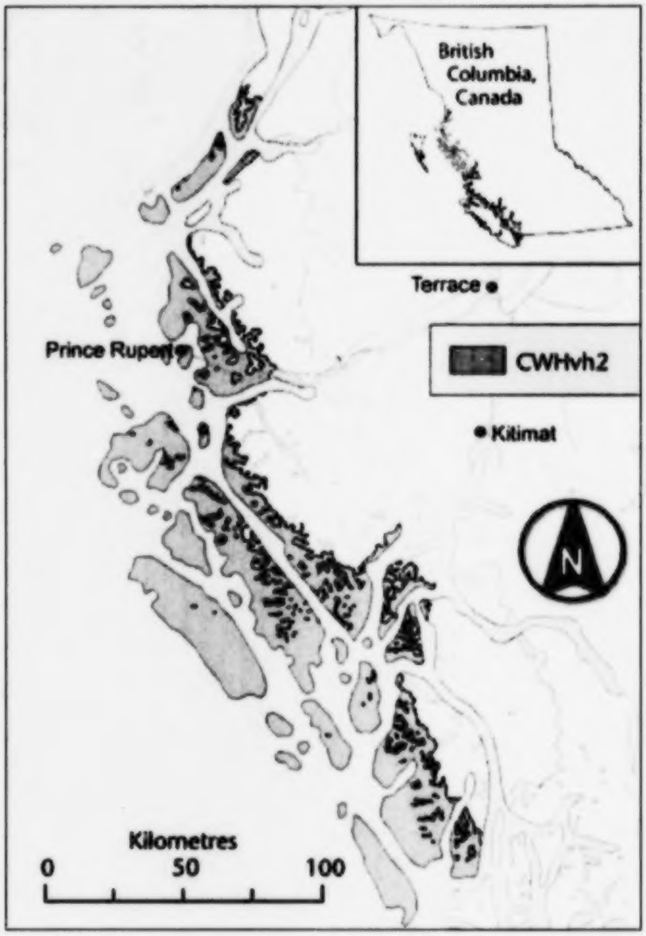

FIGURE 1.3 *Distribution of the CWHvh2 within the North Coast Forest District.*

In response to the Chief Forester's initial request for research in his 1995 AAC determination (Pedersen 1995) for the North Coast TSA, Ministry of Forests staff in the (then) Prince Rupert Forest Region commissioned a problem analysis (Kayahara and Klinka 1997). A proposal was then submitted to Forest Renewal BC that outlined plans to carry out research and to develop ecologically based operational guidelines for timber harvesting in the western redcedar–western hemlock forests on the outer coast. Forest Renewal BC approved funding for the project in May 1997. The resulting HyP³ Project has used site-specific studies and operational trials to better understand the area's ecology, silviculture, and hydrology, and broader classification and inventory studies to identify the potentially operable portion of the land base.

In the problem analysis, Kayahara and Klinka (1997) also identified the higher-elevation ecosystems of the Mountain Hemlock (MH) biogeoclimatic zone as another possible area of future operability, but operating in the MH zone was clearly a separate issue requiring its own study. Therefore, the HyP³ initiative was limited to the Coastal Western Hemlock Very Wet, Hypermaritime subzone, Central variant (CWHvh2, Figure 1.3) and did not address issues of sustainable harvesting in the MH zone.

Timber inventories usually identify lower-productivity forests on the outer north and central coast as CwYcPl931P,[6] 921P, or 921L stands, and rate them as "inoperable." The forest sites of interest

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[6] Codes used on forest inventory maps indicate: species (Cw = western redcedar; Yc = yellow-cedar; Pl = shore pine); age class (9 = greater than 250 years old); height class (2 = 10.5–19.4 m; 3 = 19.5–28.4 m); stocking (1 = mature, greater than 76 stems per hectare); and site class (P = poor; L = low; recently replaced by calculated or estimated site index).

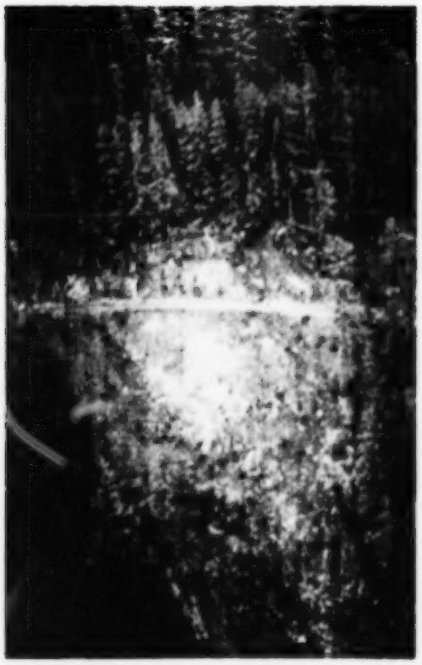

FIGURE 1.4 *Landslide associated with mid-1980s road-building activities, coastal British Columbia.*

for this research occur mainly within the CWHvh2 and typically have wet soils with thick surface organic layers (forest floors). Research in north coastal British Columbia and southeast Alaska suggests that productive forests can develop into bogs through a process of organic matter accumulation over mineral soils (**paludification**) (Banner et al. 1983; Kayahara and Klinka 1997); therefore, the effect of timber harvesting in promoting or combating this process, and thus influencing second-growth productivity, is of particular interest.

Experience in coastal British Columbia, Haida Gwaii/the Queen Charlotte Islands, and southeast Alaska has demonstrated that timber harvesting and associated activities (e.g., road building; Figure 1.4) on steeper slopes increase the likelihood of landslides, which in turn can increase the sediment input into streams (Kayahara and Klinka 1997). Slope stability issues are less of a concern within the lower-productivity stands on gentler terrain; however, access, road building, and forest regeneration in areas of wet, organic soils are significant concerns. Not only does the potential for sediment loading of streams persist, but a host of hydrological changes may effect root zone saturation, nutrient dynamics, and ultimately, forest productivity. The nature, rate, and extent of such changes have not been documented for this type of environment, so these processes are poorly understood. Finally, expanding the operable land base into lower-productivity stands could lead to a substantial expansion of harvested areas across the landscape and could significantly affect non-timber values, such as wildlife, biodiversity, and visual quality.

1.2 HyP^3 Research Approach

The HyP^3 Project is an integrated, multidisciplinary study of the coastal blanket bog–upland forest complex of the CWHvh2. We are working toward developing a better understanding of these ecosystems, as well as assessing the feasibility of harvesting these areas responsibly and sustainably, and providing management guidelines for doing so. With this in mind, we used a combination of scientific studies, operational trials, and inventory techniques to address our four project goals.

Intensive, site-specific studies have been carried out along two old-growth transects located near Prince Rupert. These transects include representative examples of the full range of ecosystems studied, from productive forests to blanket bogs. Researchers have conducted studies along these common transects to maximize co-operation among disciplines. This co-operative approach has helped to develop a better understanding of how one ecosystem component, such as hydrology, relates to others such as soil ecology or site productivity.

The more extensive aspects of the study occur on a range of sites throughout the North Coast Forest District. For example, operational trials are under way at Oona River on Porcher Island, 40 km south of Prince Rupert, and near Port Simpson on the Tsimpsean Peninsula, north of Prince Rupert. Classification and inventory work is ongoing throughout the District.

The project is organized into the following four components, which are addressed in separate chapters of this report.

1. **Hydrology and Biogeochemistry (Chapter 3)**
    - Document the watershed, soil hydrology, and biogeochemistry of the blanket bog–upland forest complex.
    - Predict how disturbances from forest harvesting can affect soil and watershed hydrology, forest succession, and regeneration.
2. **Ecosystem Processes (Chapter 4)**
    - Document relationships among soil chemical, biological, and physical characteristics, and **site series** and tree productivity.
    - Examine selected biological processes, such as soil respiration, litter decomposition, and organic matter dynamics (rates of forest floor and peat accumulation; soil faunal and microbial activity), in relation to forest productivity and bedrock type.
    - Examine the potential for manipulating soil characteristics, through harvesting and site treatments, to improve second-growth tree productivity.
    - Document past and present ecological succession in the area in relation to peat development, and determine how this is linked to site hydrology and geochemistry, as well as productivity and ecosystem development.
3. **Classification and Inventory (Chapter 5)**
    - Describe the range of ecological site characteristics associated with the target forest types, and determine their operational significance.
    - Examine the use of **Predictive Ecosystem Mapping** (PEM) to identify stands with the highest potential for timber management.
    - Identify rare and sensitive components of biodiversity (species and ecosystems) that could be at risk from forest harvesting.
    - Estimate growth and productivity across the spectrum of site series in the CWHvh2.
    - Develop baseline information on the patterns of regeneration and growth in both old-growth and second-growth stands on low-productivity sites.
4. **Operational Research Trials (Chapter 6)**
    - Develop and implement a strategy for testing harvesting and silvicultural approaches in target forest types.
    - Complete the assessment of the Port Simpson mounding trial, which was established in 1990.
    - Establish additional operational harvesting trials within the North Coast TSA to better define operability limits.

Chapter 7 provides management interpretations for cedar–hemlock ecosystems and outlines further research needs.

1.3 Previous Studies: Historical Perspective

1.3.1 Early ecological studies

Documented ecological studies of the bogs and forests of the west coast of British Columbia go back to the early 1900s (Rigg 1914, 1917, 1925, 1940; Rigg and Thompson 1922; Osvald 1933). These earliest studies were mostly carried out in Washington, Oregon, southwestern British Columbia, and southeast Alaska, and concentrated on descriptions of the vegetation, peat stratigraphy, and successional relationships of non-forested bog ecosystems. Williston (2003a) summarized the history of botanical collecting and research that has occurred on the north coast since the expeditions of Franz Boas and George Dawson in the late 1800s.

1.3.2 Ecosystem classification and related studies Beginning in the late 1950s, V.J. Krajina and many of his graduate students undertook extensive ecosystem classification studies on the west coast. Once again, these were mainly carried out on the south coastal mainland and Vancouver Island (Mueller-Dombois 1959, 1965; Lesko 1961; Orloci 1961, 1964; Wade 1965; Cordes 1972; Kojima and Krajina 1975; Klinka 1976). During this time, Krajina proposed the biogeoclimatic approach to ecological zonation of the entire province, and produced the first maps of biogeoclimatic zones (Krajina 1959, 1965, 1969). Spilsbury and Smith (1947), however, carried out forest site classification studies in the south coastal area of the province before Krajina and his students began their work, and first proposed the use of site classification to describe site quality (forest productivity) and ensure "sustained yield forestry" in British Columbia.

By the mid-1970s, the **biogeoclimatic ecosystem classification** (BEC) system had been adopted by the B.C. Ministry of Forests as a framework for forest management. This Ministry's Research Branch embarked on a province-wide classification program and recruited ecologists, botanists, soil scientists, and foresters to further develop and refine BEC. This included the development of tree species selection guidelines and other management interpretations in each of the six forest regions which existed at that time. The coast classification work began in the former Vancouver Forest Region in southwestern British Columbia (Klinka et al. 1979, 1980). In 1976, ecosystem classification work began in the coastal portions of the Prince Rupert Forest Region, which then encompassed the Mid-Coast, North Coast, and Queen Charlotte Island forest districts. Since that time, extensive ecological sampling has occurred, and reports, theses, maps, and field guides produced which describe the biogeoclimatic units and site units—both forests and wetlands—of coastal British Columbia (Yole et al. 1982; Banner 1983; Banner et al. 1983, 1986, 1987, 1988, 1989, 1993; Banner and Pojar 1987; Pojar et al. 1988; McLennan and Mamias 1992; Green and Klinka 1994; Klinka et al. 1995; Nuszdorfer and Boettger 1994; MacKenzie and Moran 2004). During this period, forest companies were also carrying out ecosystem classification work within some of the coastal Tree Farm Licences (TFL) (e.g., Lewis 1982; Beese 1983).

In 1981, the Royal British Columbia Museum sponsored an expedition to the Brooks Peninsula on northern Vancouver Island to document the natural and human history of the area, and to examine the evidence for a glacial refugium on the peninsula (Hebda and Haggarty 1997). Vegetation and soil studies on the peninsula highlighted the similarities between this hypermaritime "appendage" on northern Vancouver Island and the blanket bog–upland forest complex of the outer coastal lowlands and nearshore islands of the mainland coast to the north (Hebda et al. 1997; Maxwell 1997).

The HyP^3 Project has focused primarily on the most hypermaritime portions of the Coastal Western Hemlock Zone. The unique character of this area—its preponderance of blanket bogs and lower-productivity "boggy" forests—has sparked controversy about whether it should be included within the CWH zone, or separated out as a distinct zone. Much of this controversy stems from the difficulties faced in assessing the relative roles of climate and landscape factors (e.g., subdued topography, lack of glacial deposits, dominance of igneous intrusive bedrock geology) in controlling ecosystem development and distribution on the outer coast. Pojar and Annas (1980) proposed that this area should be considered a distinct zone, the Coastal Cedars–Pine–Hemlock (CCPH) Zone, and for several years it maintained this zonal status within the Ministry of Forests BEC system. During the 1980s, a comprehensive correlation of coastal biogeoclimatic and site units and reassessment of plot data helped to determine that the zonal ecosystem within the "CCPH" was not sufficiently different from other CWH zonal ecosystems to differentiate the area as a separate zone. Though the controversy continues, the unique blanket bog–upland forest complex that characterizes the outer coast is currently included as a very wet, hypermaritime subzone of the CWH zone (CWHvh).

1.3.3 Ecological studies in southeast Alaska The forest and wetland ecosystems of north coastal British Columbia and southeast Alaska are very similar in nature. Zach (1950) recognized the apparent tension between forest growth and bog development in southeast Alaska, and was the first to question whether "muskeg," rather than upland forest, represented the true **climax** ecosystem. We have drawn on several other Alaskan studies to help understand the relationships between vegetation and environment along north coastal British Columbia (Lawrence 1958; Stephens et al. 1970; Neiland 1971). Neiland's work (1971) is the most comprehensive treatment of these relationships within the "Forest–Bog Complex" of southeast Alaska. Most of the ecosystems described by Neiland occur along the north and central coast, though some significant differences are evident, such as the lack or scarcity of amabilis fir and western redcedar in southeast Alaska. Recent descriptions of the "ecological subsections" of southeast Alaska (Nowacki et al. 2001) also illustrate that, despite differences in classification concepts and nomenclature, our CWHvh subzone in British Columbia extends north into Alaska. Both British Columbian and Alaskan researchers agree that ecosystem classification concepts and units must be correlated between the two jurisdictions (D. D'Amore, U.S. Department of Agriculture, Juneau, Alaska, pers. comm., Dec. 2004).

1.3.4 Palynological studies With the aim of reconstructing past vegetation and climate history, the coastal bogs and other wetlands of the Pacific coast have been the subject of considerable palynological (i.e., study of the pollen record in peat and sediment profiles) investigation over the last 60 years. While many of these studies have concentrated on describing broad regional trends in vegetation and climate change since the last glacial retreat (Heusser 1960; Mathewes and Heusser 1981; Hebda 1995), others have emphasized more localized interpretation of pollen profiles to reconstruct successional sequences in the vicinity of specific sampling sites (Hebda 1977; Banner et al. 1983; Turunen and Turunen 2003). The latter approach has helped shed light on the successional relationships between bogs and forests on the north coast. This palynological evidence, in combination with studies of soil profiles and natural disturbance events such as windthrow (Ugolini and Mann 1979; Bormann et al. 1995), suggests that paludification, which results from impeded drainage and moss encroachment of forested sites on mineral soils, is an important soil-forming process on the outer coast, and has significant implications for forest productivity (Banner et al. 1983; Klinger 1990).

1.3.5 Forest management research

Because of the dominance of lower-productivity sites on the outer north coast, the question of their potential contribution to the operable land base has been discussed for many years. In 1975, a research project was initiated by the Prince Rupert Forest Region with the following objective: "... using soil investigations and various studies of plant ecosystems, produce a map which will indicate the potential productivity of a site or whether it is possible to improve it for economic gain" (B.C. Ministry of Forests 1975). Although a small cedar-poling trial was established in the Lachmach Valley in 1975, changing staff priorities led to the shelving of this project in 1978; however, prompted by a high demand for cedar and perceived future interest in expanding the operable land base into these lower-productivity cedar-types, this same issue resurfaced 15 years later. In 1990, a project funded by South Moresby Forest Replacement Account (SMFRA) was initiated at Port Simpson to look at mounding as a site treatment to improve productivity in cedar-hemlock forest types (Beaudry et al. 1994). A sister project was also established on Haida Gwaii/the Queen Charlotte Islands that built upon the initial work of Green (1989) who studied site–forest productivity relationships in lowland ecosystems on eastern Graham Island.

In 1997, after the completion of a problem analysis of the issue (Kayahara and Klinka 1997), we decided to expand the Port Simpson research into a more integrated investigation of the ecological patterns and processes within the coastal blanket bog–upland forest complex. The HyP^3 Project was initiated with Forest Renewal BC funding obtained in 1997, and the Port Simpson study became part of this larger integrated research project.

On northern Vancouver Island, a related management issue dates back to the 1960s when considerable areas of old-growth western redcedar–western hemlock forests were harvested and regenerated with redcedar, hemlock, and Sitka spruce. Regeneration problems emerged, especially with Sitka spruce. After several years of acceptable growth, this species began to show severe nutrient deficiencies and steadily declining growth rates. These symptoms were not evident in adjacent second-growth western hemlock–amabilis fir stands that originated from a widespread 1906 windstorm. Comparison of these two forest types led to several hypotheses about the causes of poorer growth and nutrition on the cedar–hemlock sites. The Salal–Cedar–Hemlock Integrated Research Program (SCHIRP) was initiated in the early 1980s to test several of these hypotheses and to establish trials looking at the potential for various mechanical and chemical treatments to improve second-growth productivity (Prescott and Weetman 1994; Blevins and Prescott 2002).

Some notable differences exist between the forest ecosystems on northern Vancouver Island and those on the mainland coast to the north.

- Yellow-cedar and mountain hemlock occurring on the outer north coast commonly extend to sea level, whereas further south both species are typically restricted to montane and subalpine forests.
- Cedar–hemlock forests that dominate the north coast tend to be lower in productivity and generally wetter than those on northern Vancouver Island.
- Salal (*Gaultheria shallon*) is less dominant and less vigorous on the north coast than on northern Vancouver Island, although other ericaceous shrubs (mainly *Vaccinium* spp.) are common in the understories of north coast forests.

- Glacial deposits (till, outwash), which are typical of northern Vancouver Island, are relatively uncommon on the north coast, with most soils developing from weathered bedrock, **colluvium**, or organic material.

Many of the results from SCHIRP and other northern Vancouver Island studies (Douglas and Courtin 2001) are undoubtedly applicable to more northern ecosystems; however, ecological differences between the two areas (CWHvm1 and CWHvh1 on northern Vancouver Island vs. CWHvh2 on the outer central and north coast) are significant enough that directly extrapolating harvesting and regeneration experience from the south to the north coast would not be appropriate. The HyP^3 Project has thus built on existing information from SCHIRP by establishing additional studies on the north coast where, to date, we have had relatively little experience with second-growth management of lower-productivity forests.

Recent literature shows that forest managers in southeast Alaska are also concerned about the limits of sustainable forest operability. Studies of forest productivity on transitional "forested wetlands" conclude that these forests meet the "minimum standard for commercial timberland," but also recognize that managing these areas for timber production presents many ecological and operational challenges (Duncan 2002; Julin and D'Amore 2003). Over the past 20 years, joint field trips with colleagues in southeast Alaska have highlighted that British Columbia shares many of the same forest management issues, and that significant potential exists for co-operation in research efforts.

2.1 Location, Physiography, and Geology

The geographic scope of the HyP^3 Project encompasses the Coastal Western Hemlock zone, Very Wet Hypermaritime subzone, Central variant (CWHvh2) within the North Coast and North Island – Central Coast forest districts of the Coast Forest Region. The CWHvh2 includes all coastal islands and a mainland fringe along the central and north coast of British Columbia, from Smith Inlet in the south to the Alaska border in the north (Banner et al. 1993) (Figure 1.3). Although the CWHvh2 also occurs on the westernmost Queen Charlotte Ranges and Skidegate Plateau on Haida Gwaii/the Queen Charlotte Islands, our HyP^3 studies did not include these areas. The study area lies primarily within the traditional territory of the Tsimshian on the north coast, but also extends into the territories of the Nisga'a, Haisla, Heiltsuk, Nuxalk, and Oweekeno First Nations.

The CWHvh2 occurs in the Hecate Lowlands and westernmost Kitimat Ranges physiographic regions (Holland 1976), and extends from sea level to approximately 600 m elevation. The Hecate Lowlands form part of the Hecate Depression, and encompass a low-lying strip of subdued and rocky terrain along the outer coast, extending inland to an elevation of approximately 600 m. The Kitimat Ranges are eroded, predominantly granitic, mountains that rise to an elevation of 2300 m to the east of the Hecate Lowlands, and are part of the Coast Mountains physiographic region (Holland 1976).

The geology of the north and central coast is complex and fragmented with numerous bedrock types, but dominated by plutonic and metamorphic groups (Figure 2.1). Plutonic rock, mostly quartz diorite and granodiorite, is the most common bedrock type encountered in the area. The regions of metamorphic bedrock are more scattered and are a complex mixture of rock types, mostly schist and gneiss (Hutchison et al. 1979). Areas dominated by granitic bedrock include Princess Royal Island, Ecstall River, southern Grenville Channel, and Fitz Hugh Sound. Areas of metamorphic bedrock include Khutzeymateen Inlet, Tsimpsean Peninsula, Kaien Island, and northern Grenville Channel. Localized areas of limestone occur on the coast, mostly in association with metamorphic bedrock. Highly mixed geology characterizes Stephens, Porcher, Banks, Pitt, and Aristazabal islands; Rivers Inlet; and Smith Sound (Hutchison et al. 1979; Roddick et al. 1979).

Although most of the north and central coast was glaciated during the last ice age, glacial deposits are rare. This is likely due to a combination of high precipitation and steep topography (at least inland of the Hecate Lowlands) resulting in the erosion of deposits into the valley bottoms, and then into the sea (Hutchison 1967). The dominant surface materials are bedrock, **saprolite**, colluvium, and organic deposits. Colluvium is more common in the steeper Kitimat Ranges, and organic deposits are more common on the gently rolling topography that dominates the Hecate Lowlands where drainage is poor (Valentine et al. 1978).

2.2 Climate

The climate of the outer north and central coast is oceanic, characterized by mild temperatures, high rainfall, and low evapotranspiration (Table 2.1). The winters are extremely wet and relatively mild; sub-zero temperatures may occur for short periods when cold, arctic air covers the area. In general, the Pacific Ocean moderates temperatures throughout the year, and the Coast Mountains serve to protect the outer coast from cold winter and hot summer continental air masses (Banner and Pojar 1987). The Coast Mountains also promote orographic rainfall, making areas closer to the mountains wetter than those on the offshore islands (Environment Canada 1998).

For the most part, precipitation occurs as rain, with little snowfall and many days of fog. With an average of over 220 days per year of recorded rainfall, prolonged dry sunny periods are rare (Environment Canada 1998). Soils in this wet environment are made even wetter by low evapotranspiration, which results in a very high moisture surplus during the growing season. This moisture surplus likely has a greater influence on plant growth and distribution than does total annual precipitation (Banner and Pojar 1987).

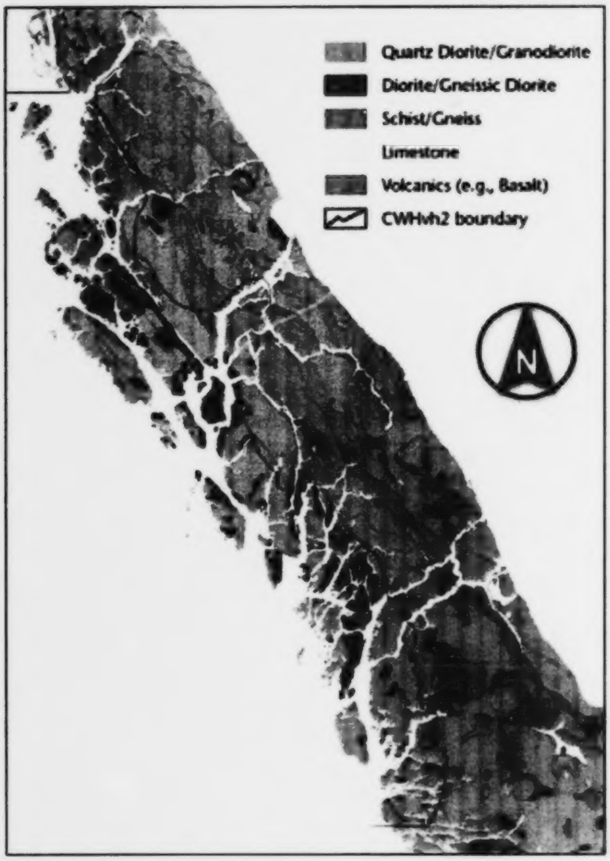

FIGURE 2.1 *Generalized bedrock geology, central and north coast of British Columbia.*

TABLE 2.1 *Climatic data for the CWHvh2 and some adjacent subzones (Banner and Pojar 1987; Reynolds 1997)*

Location and biogeoclimatic subzone	Elevation (m)	Mean annual temperature (°C)	Mean temperature warmest month (°C)	Mean temperature coldest month (°C)	Mean annual precipitation (mm)	Mean annual snowfall (cm)	Number of days with rainfall > 0.2 mm
Prince Rupert, CWHvh2	34	6.7	13.1	–0.2	2523	152	233
Bonilla Island, CWHvh2	16	8.0	13.2	2.8	2104	62	222
Ethelda Bay, CWHvh2	8	7.7	13.7	1.9	3186	144	235
McInnes Island, CWHvh2	25	8.5	14.3	2.9	2558	98	233
Kitimat, CWHvm1	128	6.4	15.9	–4.5	2299	548	195
Ocean Falls, CWHvm1	5	8.1	16.1	0.2	4387	155	218
Stewart, CWHwm	5	5.2	14.5	–5.2	1851	556	164
Alice Arm, CWHws1	314	4.5	14.1	–5.8	2074	841	n/a
Kemano Kildala Pass, MHmm1	1609	–1.4	6.9	–8.5	2793	1816	n/a

2.3 Vegetation, Soils, and Ecosystems

The vegetation of the outer north coast is a complex of productive forests, lower-productivity forests, bog forests, bog woodlands, and blanket bogs (Figures 2.2–2.6). The latter three are considered wetlands or wetland-like ecosystems and cover more than 50% of the landscape (Banner et al. 1988, 1993). The disturbance regimes characteristic of the outer coast have led to a regeneration process dominated by gap dynamics in these forests. As a result, most forests are old growth with an uneven age structure (Lertzman et al. 1996) dominated by shade-tolerant conifers, such as western hemlock and western redcedar (Banner et al. 1993).

The major tree species on the outer coast are western redcedar, western hemlock, yellow-cedar or cypress, shore pine, Sitka spruce, amabilis fir, mountain hemlock, and red alder (*Alnus rubra*) (Banner et al. 1993). Both yellow-cedar and mountain hemlock are found from sea level to subalpine elevations in the CWHvh2 (mostly in lower-productivity forests and bogs at lower elevations), whereas these species are restricted to higher elevations in south coastal British Columbia.

Average or **"zonal" sites** (i.e., sites that reflect the overriding influence of regional climate) in the CWHvh2 are much wetter than zonal sites in any other subzone in British Columbia. The forests are open and scrubby, and are dominated by western redcedar, yellow-cedar, and western hemlock; shore pine and mountain hemlock occur in variable amounts. Forest productivity (normally expressed as **site index**) on zonal sites is often low compared to zonal sites found in other Coastal Western Hemlock subzones (Banner et al. 1993). The shrub layer is usually well developed, and is dominated by salal (*Gaultheria shallon*), blueberry (*Vaccinium* spp.), and false azalea (*Menziesia ferruginea*). Common species in the herb layer include bunchberry (*Cornus canadensis*), deer fern (*Blechnum spicant*), false lily-of-the-valley (*Maianthemum dilatatum*), heart-leaved twayblade (*Listera cordata*), and skunk cabbage (*Lysichiton americanum*). The moss layer is dominated by lanky moss (*Rhytidiadelphus loreus*) and step moss (*Hylocomium splendens*), though common green sphagnum (*Sphagnum rubiginosum* and *S. girgensohnii*) and large leafy moss (*Rhizomnium glabrescens*) are often found. Productive forests are located mainly on moderate to steep, often colluvial, slopes with good drainage, and on floodplains; areas of productive forest are typically interspersed with lower-productivity forests and open bogs (Banner et al. 1993). The forested site series of the CWHvh2 and their position on the edatopic grid (Banner et al. 1993)

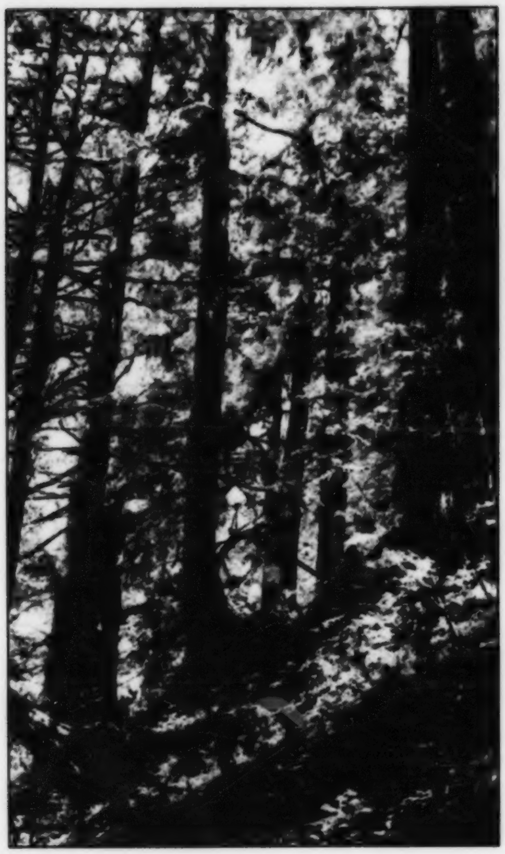

FIGURE 2.2 *Upland productive forest type, CWHvh2/06.*

FIGURE 2.4 *Bog forest type, CWHvh2/11.*

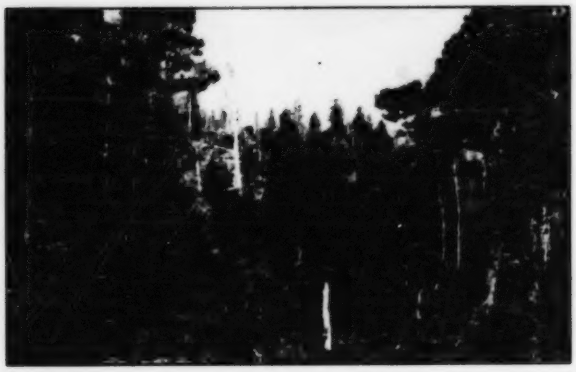

FIGURE 2.5 *Bog woodland forest type, CWHvh2/12.*

FIGURE 2.3 *Upland scrub forest type, CWHvh2/01.*

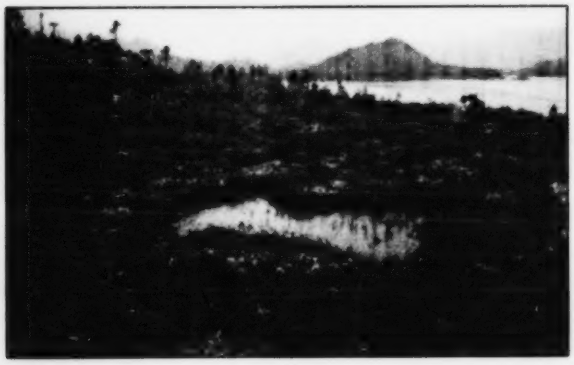

FIGURE 2.6 *Blanket bog, CWHvh2/32.*

are depicted in Figure 2.7. Detailed descriptions of these site series can be found in Chapter 5 (section 5.2).

The soils of the forested portion of the CWHvh2 are imperfectly drained **Podzols** and **Folisols** with deep surface organic layers. Wetland organic soils (Fibrisols, Mesisols, and some Humisols) are also common. **Brunisols** and **Regosols** can be found on floodplains, and **Gleysols** are common on wet sites where mineral horizons remain saturated for extended periods (Banner et al. 1993). Whatever the soil type, their formation and composition are influenced greatly by the underlying bedrock geology. Because of a lack of glacial till in this area, mineral soils are largely formed from decomposed bedrock (saprolite) or from colluvium. Bedrock types vary greatly in their resistance to weathering (Valentine et al. 1978) and thus in their rate of decomposition and nutrient release. For example, plutonic granitic bedrock is the most resistant to weathering and gives rise to relatively thin, nutrient-poor mineral soils compared with metamorphic rocks (Kranabetter and Banner 2000; see section 4.5.1). Climate is also very important in soil formation, with high rainfall leading to strongly leached, nutrient-deficient Podzolic mineral soils. The extreme amount of moisture experienced in the hypermaritime environment contributes to the saturated, **anaerobic** soil conditions that promote moss growth and hinder decomposition of organic matter; such conditions result in thick accumulations of organic forest floor materials (Banner et al. 1993). Consequently, on much of the outer coast where the terrain is gentle, organic materials have accumulated to form extensive peatland areas (Figure 2.8). These peatlands usually contain a scrubby or sparse tree layer in a mosaic of open bogs, bog woodlands, and bog forests. Peat depth varies from less than 50 cm on the most exposed outer coastal islands to several metres in some areas near Prince Rupert.

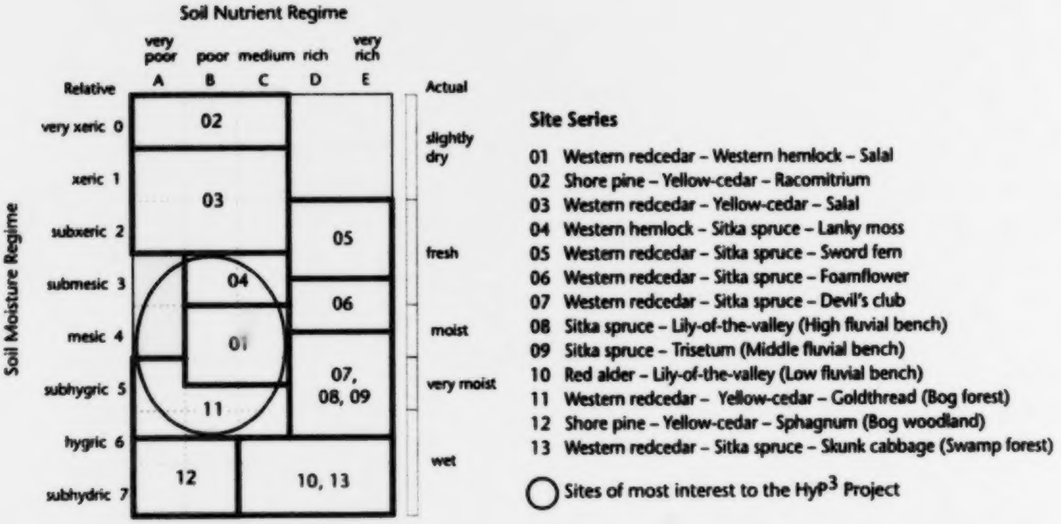
Soil Nutrient Regime
very poor
poor
medium
rich
very rich
Relative
A
B
C
D
E
Actual
very xeric 0
xeric 1
subxeric 2
submesic 3
mesic 4
subhygric 5
hygric 6
subhydric 7
Soil Moisture Regime
slightly dry
fresh
moist
very moist
wet
02
03
05
04
06
01
07, 08, 09
11
12
10, 13
Site Series
01 Western redcedar – Western hemlock – Salal
02 Shore pine – Yellow-cedar – Racomitrium
03 Western redcedar – Yellow-cedar – Salal
04 Western hemlock – Sitka spruce – Lanky moss
05 Western redcedar – Sitka spruce – Sword fern
06 Western redcedar – Sitka spruce – Foamflower
07 Western redcedar – Sitka spruce – Devil's club
08 Sitka spruce – Lily-of-the-valley (High fluvial bench)
09 Sitka spruce – Trisetum (Middle fluvial bench)
10 Red alder – Lily-of-the-valley (Low fluvial bench)
11 Western redcedar – Yellow-cedar – Goldthread (Bog forest)
12 Shore pine – Yellow-cedar – Sphagnum (Bog woodland)
13 Western redcedar – Sitka spruce – Skunk cabbage (Swamp forest)
○ Sites of most interest to the HyP³ Project

FIGURE 2.7 *Edatopic grid depicting forested site series of the CWHvh2 subzone (Banner et al. 1993). Circled site series (04, 01, and 11) are of most interest to the HyP*^{3} *Project.*

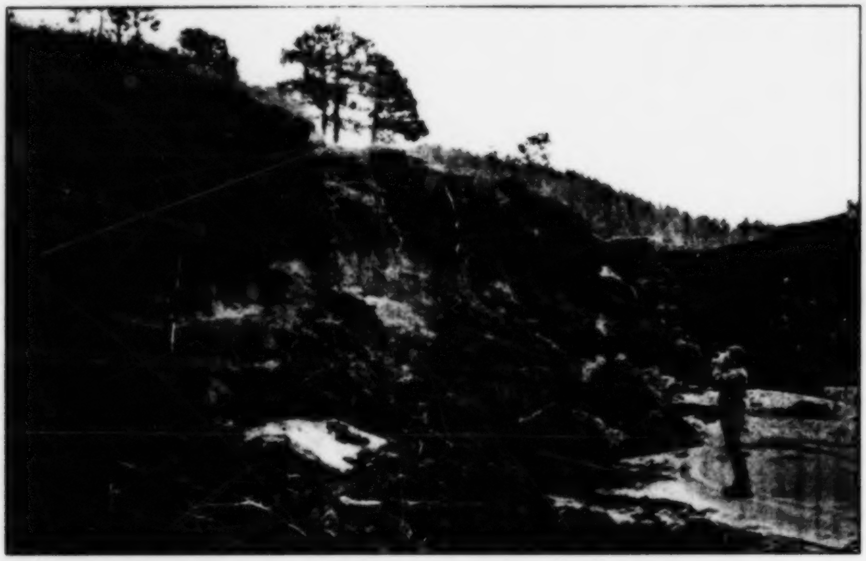

FIGURE 2.8 *Open bog development on 2 m of accumulated peat near Prince Rupert.*

2.4 Natural Disturbance Regimes

Disturbance histories are distinctly different within the CWHvh2 between forests on the steep slopes of the Kitimat Ranges and those on the gently rolling terrain of the Hecate Lowlands. In general, high forest productivity is associated with well-drained and aerated sites on steep slopes, often with a history of natural disturbance by landslide or windthrow events over the past several hundred years. These disturbance events tend to mix soil layers, slowing the buildup of surface organic material, exposing mineral soil, and improving nutrient availability (Bormann et al. 1995). More frequent natural disturbances also occur on the floodplains of larger rivers (e.g., the Skeena), as well as on smaller more confined systems. Fluvial disturbance by flooding can occur annually or every few years, depending on bench height and weather conditions.

In contrast to productive forests on steep slopes and floodplains, the lower-productivity cedar-dominated sites found on the Hecate Lowlands have typically gone for centuries without major disturbances. This lack of disturbance, together with much poorer drainage, has resulted in deep accumulations of organic matter and much lower levels of available nutrients (Kranabetter et al. 2003). In these forests, most disturbances are small and localized, and most gaps are created by stem breakage or blowdown events (Lertzman et al. 1996; Nowacki and Kramer 1998; Hennon and McClellan 2003). Because of the more subdued terrain, landslides are less common on the outer coast than in the Kitimat Ranges further inland. In addition, large-scale disturbance events, such as major blowdown or fire, are infrequent throughout the area (Neiland 1971; Nowacki and Kramer 1998). Return intervals for major disturbances are probably greater than 1000 years for most lower-productivity old-growth stands; however, our current estimates of disturbance return intervals are speculative, based on limited stand age data. Detailed age structure analysis over extensive areas of old-growth forest on the north coast is required to better quantify differences in disturbance regimes among the many forest types.

2.5 Adjacent Biogeoclimatic Units

The CWHvh2 is adjacent to several other biogeoclimatic units, including the Coastal Western Hemlock, Very Wet Maritime, Submontane and Montane variants (CWHvm1 and CWHvm2), the CWH Wet Maritime (CWHwm) subzone, and the Mountain Hemlock, Wet Hypermaritime, Windward variant (MHwh1).

The CWHvm1 occupies low-elevation (submontane) areas inland of the CWHvh2. These areas have a wet, humid, mild oceanic climate, but are somewhat colder in the winter and warmer in the summer than the CWHvh2. Amabilis fir is more common than in the CWHvh2, and mountain hemlock and yellow-cedar are uncommon (Banner et al. 1993).

The CWHvm2 occupies higher-elevation (montane) areas above the CWHvm1 (above 350 m elevation). The CWHvm2 has a shorter growing season and deeper snowpack than the CWHvh2 and CWHvm1. Western redcedar and shore pine are uncommon in this subzone. Subalpine fir (*Abies lasiocarpa*) is occasionally found in the eastern-most CWHvm2, mostly in areas of cold air drainage, while yellow-cedar and mountain hemlock increase in abundance from the CWHvm1 to vm2 (Banner et al. 1993).

The CWHwm is the most northerly CWH subzone. It is characterized by steep rocky terrain, very heavy snowfall, and lower plant species diversity. Western hemlock and Sitka spruce are the dominant tree species, with amabilis fir rare or absent, and yellow-cedar and western redcedar infrequent (Banner et al. 1993).

The subalpine MHwh1 is found above the CWHvh2 on the coastal islands and adjacent low-lying mainland. The MHwh1 is characterized by heavy snowfalls, a short growing season, the dominance of yellow-cedar and mountain hemlock, the scarcity of amabilis fir, and the absence of subalpine fir. The distinction between forest and parkland is vague because of the many non-forested wetlands in this subzone (Banner et al. 1993).

2.6 HyP^3 Study Sites

Although some aspects of the HyP^3 research and inventory initiatives are extensive in nature and have been carried out throughout the North Coast Forest District (e.g., Predictive Ecosystem Mapping), most of the intensive research activities have been conducted at four study sites (Figure 2.9). Studies of ecosystem function have been carried out along study transects at Diana Lake and Smith Island. These old-growth sites have been used to study hydrology and biogeochemistry, ecosystem productivity and decomposition rates, peatland development and succession, soil ecology, and old-growth forest productivity. Operational trials have been established at the Port Simpson and Oona River study areas. These operational trials have been used to study harvesting methods, silvicultural treatment options, regeneration issues (natural and artificial), log quality and utilization, and effects of harvesting on soil properties and biodiversity.

2.6.1 Diana Lake The Diana Lake study site is located within and adjacent to Diana Lake Provincial Park, 15 km southeast of Prince Rupert. Elevation ranges from 75 to 705 m. The study area contains a typical CWHvh2 cross-section of ecosystems including zonal lower-productivity forests, bog forests, bog woodlands, blanket bogs, swamps, and productive forests on steeper slopes. The most common bedrock in the area is gneissic diorite, although schist is also present in some locations. Initial studies and installation of monitoring equipment began in 1997. Ecosystem mapping and permanent plot layout were completed, and a meteorological station, which records precipitation and wind speed and direction, was installed in an open bog along one of the

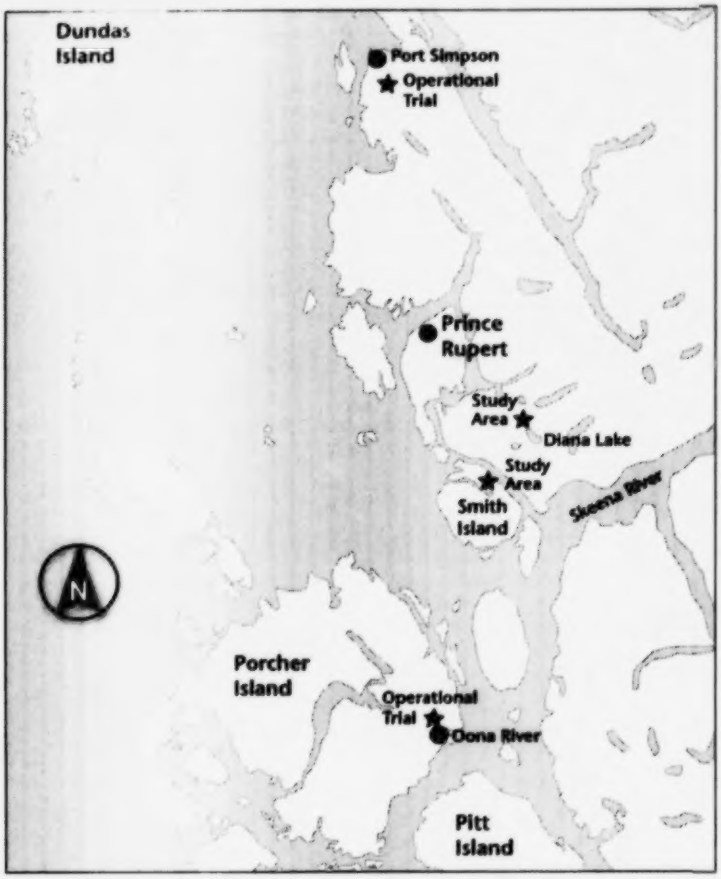

FIGURE 2.9 *Location of HyP³ intensive study sites and operational trial sites on the north coast of British Columbia.*

study transects. Timber cruising and stream surveys were completed in the summer of 2000. Hydrology, geochemistry, and moss productivity studies were carried out on a continuous basis from 1997 until the summer of 2001. Some destructive tree sampling for growth and yield purposes was also conducted at this site.

2.6.2 Smith Island The Smith Island study site is located on Smith Island in Inverness Passage at the mouth of the Skeena River, 20 km south of Prince Rupert near the community of Port Edward. The elevational range of the Smith Island site is 0–380 m. The site is dominated by lower-productivity zonal forests on gentle slopes, productive forests on steeper slopes, and bog woodlands, bog forests, and open blanket bogs. The bedrock is largely gneissic diorite with some schist. Studies were also initiated at this site in 1997 and, in keeping with the methodology established at Diana Lake, ecosystem mapping and permanent plot layout were completed and a meteorological station was installed in an open bog.

Timber cruising and stream surveys were completed in the summer of 1999. Hydrology, geochemistry, and moss productivity studies were carried out on a continuous basis from 1997 until the summer of 2001. This site was initially considered for harvest as an operational trial; however, visual quality issues, volume concerns, and the high costs associated with site accessibility made the harvesting impractical.

2.6.3 Port Simpson The Port Simpson study site is located 30 km north of Prince Rupert near the village of Port Simpson on the Tsimpsean Peninsula. The operational research trial was initiated in 1990 and incorporated into the HyP^3 Project in 1997. The area is underlain by schist bedrock and was dominated by lower-productivity zonal forest before it was harvested in the late summer of 1990. After harvest, the block was divided into eight plots, four to be mounded and four untreated controls. The objective of the trial was to study the effects of creating mounds by mixing the mineral soil with the surface organic horizons. The mounds were created in 1990 using an excavator, and then planted in 1991 with equal amounts of western hemlock, western redcedar, and shore pine. At intervals from 1991 to 1997, measurements of root and shoot biomass, and height and caliper were taken, and foliar analyses were conducted on the seedlings (Shaw and Banner 2001a, 2001b; see Chapter 6, section 6.2).

2.6.4 Oona River The Oona River operational research trial is located near the community of Oona River on Porcher Island, 40 km south of Prince Rupert at 0–50 m elevation. The study area comprises two adjacent cutblocks of 10.2 ha and 7.4 ha. These blocks are primarily composed of three ecosystem types: the lower-productivity zonal forest, which accounts for approximately 84% of the harvested area, and smaller patches of bog woodland and productive upland forest. The dominant bedrock at Oona River is schist. The initial block identification, layout, and ecosystem mapping for this trial began in 1998. The blocks were harvested in June 2000. Late in 2001, plots were established to test the effects of three site preparation treatments: light scarification and raking, light scarification and raking with phosphorus fertilization, and spot raking followed by mixing surface organic material with mineral soil to form low mounds. All site preparation treatments were completed using a tracked excavator. After treatments were applied, the blocks were planted with western redcedar and yellow-cedar in the spring of 2002 (LePage et al. 2002; see Chapter 6, section 6.3). Monitoring of seedling growth and nutrition began in 2003 and will continue at regular intervals.

The intensive HyP^3 study areas established to date contain good representation of CWHvh2 forest and bog ecosystems in areas of gneissic diorite and schist bedrock. The study areas were chosen, in part, because the cedar–hemlock stands on these bedrock types were considered (based on earlier ecosystem sampling) to have the greatest potential for forest management and, in part, for logistical reasons. In addition to the more intensive studies carried out at these locations, various studies involving ecosystem description, classification, and mapping, soil ecology, regeneration, and site productivity were completed at sites throughout the north coast that encompass the full spectrum of bedrock types (see Chapters 4 and 5). To compare findings with the trials on metamorphic rock and to expand the applications and management interpretations of the HyP^3 Project, plans are currently under way to establish additional operational trials in areas of granodiorite bedrock. One such study area at Rainbow Lake, near Prince Rupert, has been laid out in preparation for harvesting.

3.1 Introduction

Water plays a pivotal role in shaping ecosystem function on the outer coast. For this reason, detailed hydrological studies are an important part of the HyP^3 Project. In hypermaritime ecosystems such as these, it is critical to comprehend the relationships between water and landscape processes, as well as hydrological responses to forest management actions. Changes in both forest composition and soil properties influence hydrological responses. Forest harvesting and silvicultural treatments manipulate the forest canopy, thus affecting rainfall interception and transpiration, and the amount of water reaching the forest floor. Road building, site disturbance, and site preparation modify soil drainage patterns and the rate of water runoff. The water-driven biogeochemical processes governing nutrient availability are also influenced by altered site hydrology. An understanding of how these hydrological changes will affect long-term forest dynamics and site productivity is important in the practice of sustainable forest management.

3.2 Watershed Hydrology

Watershed hydrology is the study of water movement and storage within a unit of land that drains all water to a common outlet (Black 1996). Forest management activities can alter water movement and storage within a watershed by changing runoff timing and magnitude (Bosch and Hewlett 1982). Hydrological effects related to forest harvesting and road building include decreased canopy interception and evaporation, decreased transpiration, changes to snow accumulation and melt, and altered soil hydrology. The watershed hydrology of an area is frequently described using a "water balance" approach in which watershed inputs, storage, and outputs are measured. Water inputs are primarily rain and snow; storage is groundwater within the soil; and outputs are evaporation, transpiration, and runoff. The quantification of each of these elements within undisturbed watersheds is important to gain an understanding of how forest ecosystem disturbances will affect soil moisture, runoff, sedimentation, and paludification (bog formation). Some initial water balance research in the CWHvh2 was carried out by Beaudry and Sager (1995); the watershed hydrology studies of the HyP^3 Project were designed to expand on this work.

In mountainous areas, precipitation can increase with elevation. As moist air is lifted over a barrier, it cools and the water vapour condenses and falls. This is known as **orographic precipitation**. The relationship between precipitation and topography is complex, but is mainly affected by the prevailing wind direction, speed, and humidity. Orographic precipitation can have a significant influence on the water balance of watersheds in mountainous terrain and, therefore, it must be considered in water balance calculations.

Canopy interception plays an important role in determining the amount of rainfall reaching the forest floor. During a rainfall event, water either penetrates the canopy falling directly to the understorey or forest floor, or is intercepted by the canopy. From there it can drip to the ground surface, flow down tree stems, or be held and evaporate. The portion that falls directly to the ground or drips from the canopy is termed "throughfall." Rainfall that is intercepted and flows down the tree trunk is known as "stemflow," and the remainder is called "interception."

The amount of rainfall intercepted by a forest canopy depends on storm size, intensity, duration, weather conditions, forest structure, tree species and architecture, tree age, tree density, and epiphytic growth of mosses and lichens (Crockford and Richardson 1990; Beaudry and Sagar 1995; Calder 1998; Spittlehouse 1998). Depending on these conditions, the forest canopy may intercept 15–35% of annual rainfall.

Removal of the forest canopy in a wet environment will introduce more water to already wet soils. Potential effects of this increased water include larger peak water flows, increased erosion, and decreased slope and channel stability (Spittlehouse 1998). A higher **water table** could also result, changing the ecology of the site and leading to regeneration problems, lower tree productivity, and paludification.

3.2.1 Study approach Our methods are presented briefly here; if more detail is required, refer to the source papers (Maloney and Bennett 2002; Maloney et al. 2002; Emili 2003). Meteorological stations were set up in open bogs at both the Smith Island and Diana Lake study sites to measure precipitation and wind direction and speed. For orographic effects on rainfall, measurements were made in openings at several elevations in both watersheds, and at the sea-level site at the North Pacific Cannery in Port Edward (reference station). Throughfall was measured using ten 5-m troughs at each site (Figure 3.1). At Diana Lake, two rectangular "fog harps" strung with vertically oriented monofilament were used to measure the timing and relative magnitude of fog drip from January to August 1998.

Stemflow was measured on 17 trees at Smith Island and 15 trees at Diana Lake using 10-mm collars wrapped 1.5 times around each tree (Figure 3.2). Stream discharge was measured using a combination of continuous water level recording devices, stream gauging, and V-notch weirs (Figure 3.3). Automatic recording devices were installed on most installations. Hemispherical photography was used to determine the canopy closure above the throughfall troughs (Frazer et al. 2000). Forest stand characteristics

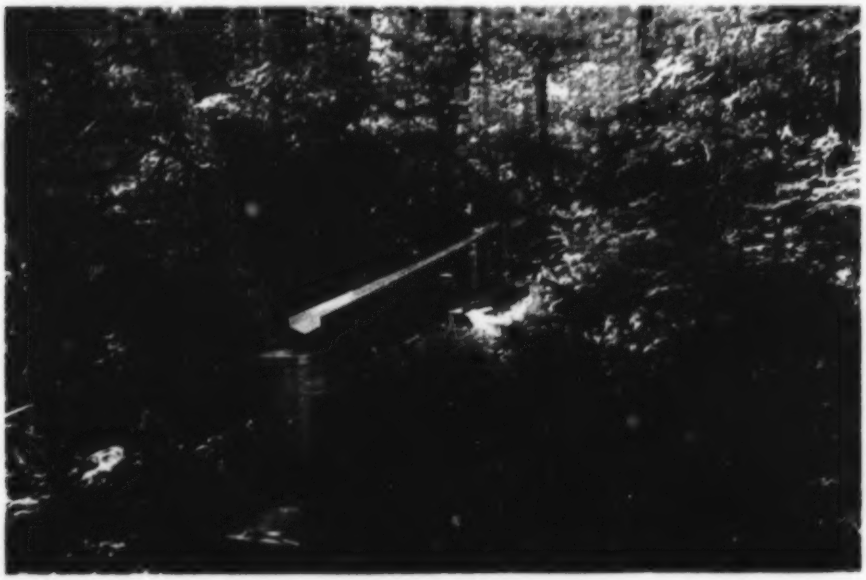

FIGURE 3.1 *Trough system used to collect rain "throughfall" data at the Diana Lake study site.*

FIGURE 3.2 *Stemflow collection system on a redcedar tree at the Smith Island study site.*

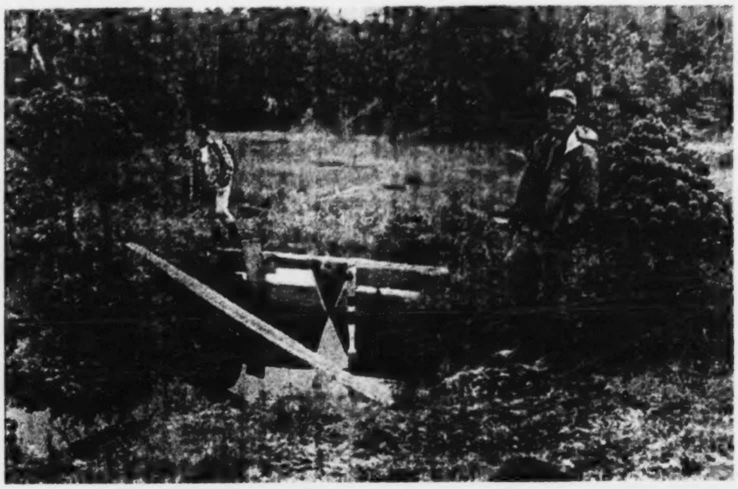

FIGURE 3.3 *V-notch weir for measuring discharge on a bog stream at Diana Lake study site.*

were measured using standard prism (variable radius) cruise plots for stems over 7.5 cm diameter at breast height (DBH), with supplemental fixed-area plots for stems under 7.5 cm DBH. For the most part, hydrological installations were maintained for 7–8 months per year (April to October or November) and thus data do not reflect annual conditions.

Water balances (or budgets) were determined for watersheds at the Smith Island and Diana Lake sites using the equation:

Precipitation =
stream discharge + evapotranspiration +/– groundwater storage

The precipitation, evaporation (assumed to equal interception), and discharge components were measured directly. Precipitation at the North Pacific Cannery was measured year-round, while precipitation at the Smith Island and Diana Lake sites was recorded from April to October or November. Stream discharge at the Smith Island and Diana Lake sites was measured year-round. The change in storage was assumed to be negligible over time periods as short as a few years, especially if the water year selected starts and ends at a time when the soil moisture is near its maximum (Dingman 2002). Transpiration was the only component that was not measured, and therefore could be calculated using the above equation; however, this calculation also contains all measurement errors and is only considered as a rough estimate of actual transpiration (Maloney and Bennett 2002). Interception was measured in forested ecosystems and thus evaporation values for the entire study watersheds were calculated by multiplying the interception values by the percentage of the watershed that was forested (vs. open bog and other non-forested areas) (Maloney and Bennett 2002).

Canopy interception was determined using the equation:

Interception =
precipitation – (throughfall + stemflow)

Hydrological response (runoff ratio) is the ratio of discharge (mm) to rainfall input (mm). **Lag time** closely approximates the time in hours from when one-half of the rainfall in the event fell to when one-half of the discharge from the event occurs.

3.2.2 Results: hydrological response and timing An analysis of 18 discrete rainfall events showed that the hydrological response and lag time for both watersheds varied with event size and the weather conditions that preceded the event. This was particularly noticeable in the hydrological response to small rainfall events following a dry period, which ranged from 0.18 to 0.21 (Figure 3.4). If a small event followed a wet period, the hydrological response almost doubled (0.32–0.38). The hydrological responses for large rainfall events varied widely regardless of the moisture conditions that preceded the rainfall event. The hydrological response for large rainfall events preceded by wet and dry conditions ranged from 0.26 to 0.81. Although small events after a wet period had a higher response than those after dry periods, the response was never as great as the maximum recorded from some large events. In addition, lag time was shortest if the rainfall event occurred within 48 hours of the previous rainfall event.

3.2.3 Results: orographic rainfall Rainfall totals at the Smith Island and Diana Lake sites were consistently higher than at the North Pacific Cannery reference site at Port Edward (Table 3.1). The high-elevation sites at Diana Lake also recorded higher totals than the Smith Island sites. Within the Diana Lake watershed, the hillslope site recorded 6.8% more rainfall than the hilltop site, even though the sites were at the same elevation. The Diana Lake high-elevation sites were 2.3 km apart on opposite sides of a valley, each with topographically different surroundings. The hillslope site was at a 337 m elevation on the leeward side (north aspect) of a 750-m mountain, while the hilltop site was on top of a 337-m hill.

Although 60% of rainfall events at both sites occurred within the 1–19.9 mm category (Figure 3.5), the greatest amount of rainfall (26%) occurred within the 20–39.9 mm category (Figure 3.6). Approximately 55% of annual rainfall resulted from events greater than 40 mm. Rainfall at both watersheds was closely linked to wind direction. Approximately 88% of total rainfall at the Diana Lake and Smith Island sites occurred with wind from the

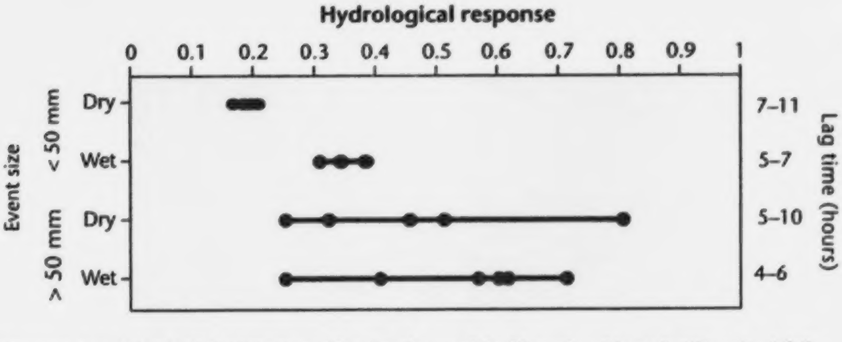

FIGURE 3.4 *Hydrological response and lag time for small (< 50 mm) and large (> 50 mm) rainfall events in the Smith and Diana watersheds. "Wet" and "dry" refer to whether or not rainfall occurred within the previous 48 hours.*

TABLE 3.1 *Total monthly rainfall by site and elevation, correlated (r) to the North Pacific Cannery reference site at Port Edward (July–October 1999 and May–October 2000)*

Site	Total measured rainfall (mm)	Difference (%)	r
Cannery (0 m)	2476	n/a	n/a
Smith (52 m)	2596	+4.9%	0.99
Smith (332 m)	2747	+11.0%	0.99
Diana Met (72 m)	2834	+14.5%	0.99
Diana south (337 m)	2979	+20.4%	0.99
Diana north (337 m)	3149	+27.2%	0.98

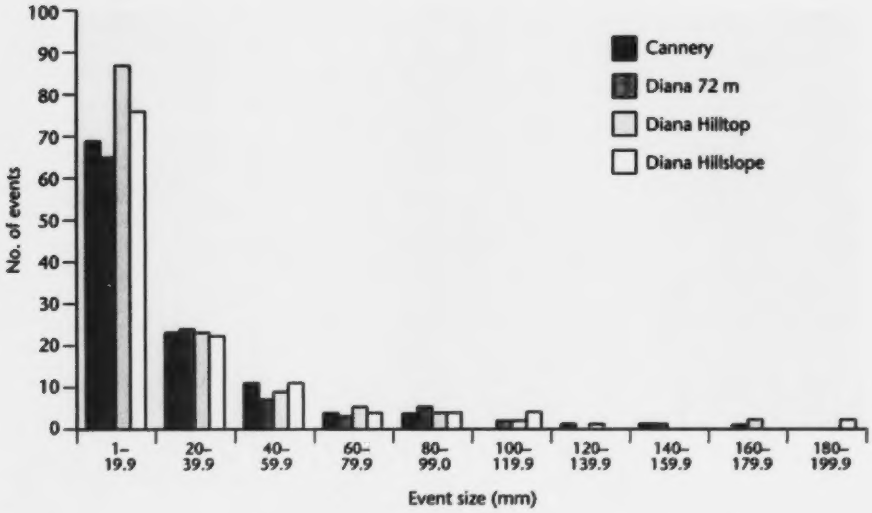

FIGURE 3.5 *Frequency distribution of rainfall events greater than 1 mm at the Diana Lake study site.*

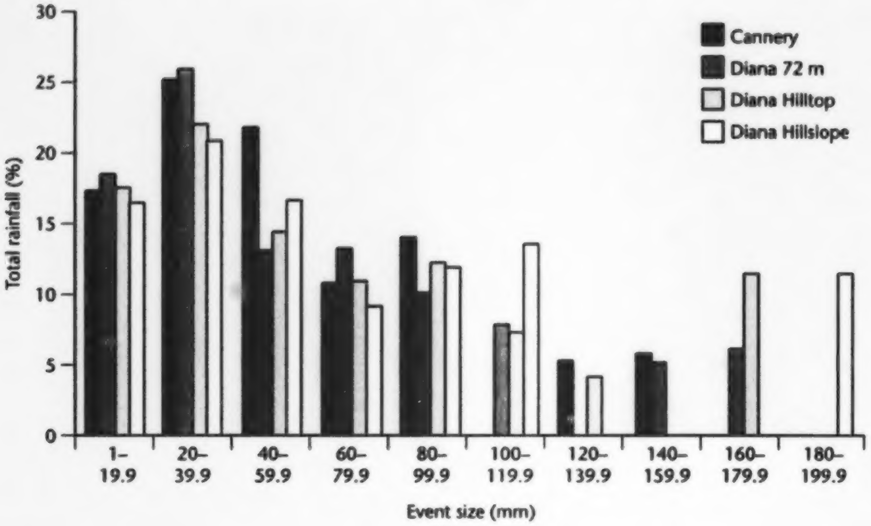

FIGURE 3.6 *Percent of total rainfall by event size category at the Diana Lake study site.*

southeast (121°) to the south-southwest (210°) (Table 3.2). All large rainfall events also occurred with wind from this quadrant.

3.2.4 Results: canopy interception, fog drip, and stemflow Over the ice-free monitoring periods from May to November, 1999–2001, an average of 1862 mm/yr of rain fell at Smith Island, and 1943 mm/yr at Diana Lake (Table 3.3). The average annual interception rate was 25% at Smith Island and 21% at Diana Lake (Table 3.3). These results are similar to those of Spittlehouse (1998), who observed interception rates of 30% for mature coastal western hemlock forests on Vancouver Island, and of Beaudry and Sagar (1995), who observed interception rates of 21% for a coastal redcedar–western hemlock forest at Port Simpson, 25 km north of Prince Rupert. Monthly interception at Smith Island ranged from 12 to 46%, and at Diana Lake from 15 to 39% (Table 3.4). Maximum interception was observed during the dry summer months, and minimum interception during the wettest months.

For individual rainfall events, interception varied from 10 to 100% (Figure 3.7). The wide range of interception is due to the size, length, and intensity of the rainfall event, and timing relative to other events. Interception decreased with both event intensity and event duration, especially for medium- and long-duration events (Table 3.5). Interception was lowest for events of long duration, regardless of intensity or canopy state. Interception was greatest, and stemflow and throughfall lowest, during low-intensity, short-duration events, regardless of the canopy saturation level. For these events, interception was roughly 62–70% at Smith Island and 69% at Diana Lake. For low-intensity, long-duration events, interception was roughly 30% at Smith Island and 22% at Diana Lake. The wet or dry condition of the canopy before the event did not have a major effect on interception. In the dry canopy, throughfall began shortly after the start of a storm event, while a delay in stemflow was evident until the canopy was saturated.

Fog drip was detected on 59% of the days during the sampling period

TABLE 3.2 *Percentage of rainfall by wind direction*

Direction	Bearing (°)	% of total rainfall						
		Diana Lake[a]				Smith Island[b]		
		Cannery	72 m	Hillslope	Hilltop	Cannery	52 m	331 m
NE Quadrant	**0.1–90**	**0.3**	**0.3**	**0.3**	**0.3**	**0**	**0**	**0**
NNE	0.1–30	0	0	0	0	0	0	0
NE	30.1–60	0	0	0	0	0	0	0
ENE	60.1–90	0.3	0.3	0.3	0.3	0	0	0
SE Quadrant	**90.1–180**	**59.8**	**61.1**	**59.5**	**60.5**	**79.8**	**79.5**	**79.0**
ESE	90.1–120	1.1	1.4	1.4	1.4	6.9	7.0	6.9
SE	120.1–150	25.4	25.0	26.4	25.2	23.5	22.9	23.0
SSE	150.1–180	33.2	34.7	31.8	33.9	49.5	49.6	49.1
SW Quadrant	**180.1–270**	**39.8**	**38.3**	**39.7**	**38.9**	**20.0**	**20.2**	**20.4**
SSW	180.1–210	29.6	28.9	30.2	29.1	14.4	14.8	14.8
SW	210.1–240	8.1	7.6	7.4	7.7	3.6	3.3	3.3
WSW	240.1–270	2.1	1.8	2.1	2.1	2.0	2.1	2.3
NW Quadrant	**270.1–360**	**0.1**	**0.3**	**0.4**	**0.3**	**0.2**	**0.4**	**0.5**
WNW	270.1–300	0.1	0.3	0.4	0.3	0.2	0.4	0.5
NW	300.1–330	0	0	0	0	0	0	0
NNW	330.1–360	0	0	0	0	0	0	0
Total rainfall (mm)		2475	2833	3149	2979	2475	2595	2745

a Cannery results calculated using Diana Lake anemometer.

b Cannery results calculated using Smith Island anemometer.

TABLE 3.3 *Annual rainfall, throughfall, stemflow, and interception at the Smith Island and Diana Lake sites (May–November, 1999–2001)*

	Smith Island				Diana Lake			
	Total rainfall (mm)	Canopy throughfall (mm)	Stemflow (mm)	Interception (mm)	Total rainfall (mm)	Canopy throughfall (mm)	Stemflow (mm)	Interception (mm)
1999	2133	1443	22.9	667	2156	1673	17.6	465
2000[a]	1793	1345	21.0	427	1800	1429	15.5	356
2001[a]	1659	1308	22.1	329	1873	1446	15.6	412
Average	1862	1366	22.0	474	1943	1516	16.2	411
%		73.4	1.2	25.5		78.0	0.8	21.2

a To account for canopy variability, the location of throughfall troughs changed to five new locations for 2000 and 2001.

TABLE 3.4 *Maximum and minimum monthly interception as a percentage of rainfall at the Smith Island and Diana Lake sites (May–November, 1999–2001)*

	Smith Island			Diana Lake		
	Total rainfall (mm)	Interception (mm)	Interception (%)	Total rainfall (mm)	Interception (mm)	Interception (%)
Maximum	515.5	62.3	12.1	607.5	91.7	15.1
Minimum	60.5	27.9	46.1	73.5	28.9	39.3

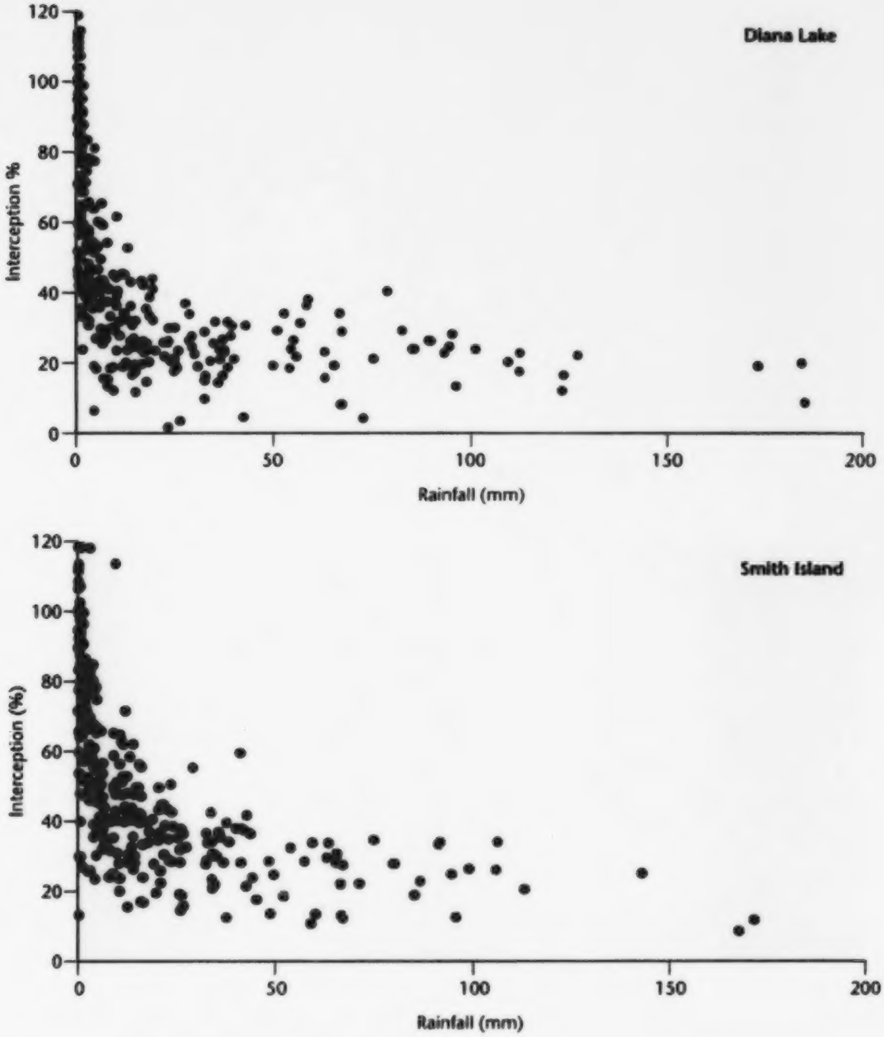

FIGURE 3.7 *Interception as a percentage of rainfall, by rainfall event, at the Diana Lake and Smith Island sites. Calculations assumed a constant stemflow of 1.2% at Smith Island and 0.8% at Diana Lake.*

TABLE 3.5 *Rainfall interception sorted by canopy condition, event intensity, and event length*

			Smith Island		Diana Lake	
Canopy condition	**Intensity (mm/hr)**	**Event length (hrs)**	***n***	**Interception average (%)**	***n***	**Interception average (%)**
Wet (< 24 hrs without rain)	Low (≤ 1 mm/hr)	< 5	117	62	78	69
		5–24	109	41	104	30
		> 24	29	30	19	22
	High (> 1 mm/hr)	< 5	6	37	4	28
		5–24	38	24	26	17
		> 24	31	19	32	18
Dry (> 24 hrs without rain)	Low (≤ 1 mm/hr)	< 5	45	70	20	69
		5–24	21	41	24	28
		> 24	4	30	6	21
	High (> 1 mm/hr)	< 5	0	–	2	43
		5–24	14	28	11	24
		> 24	9	23	11	19

(January–August 1998) and 99% of this occurred during rainfall events. However, with the type of collectors used in this study, it was difficult to differentiate the contributions of fog, drizzle, and rain. Compared with studies of fog drip in other coastal forests (Azevedo and Morgan 1974; Harr 1982), the amount of fog drip, as indicated by throughfall in the absence of rainfall, was lower than expected in these north coast forests. Nevertheless, cloudwater or fog drip inputs may be more substantial at higher elevations or at more exposed locations on the north coast; fog could thus be a significant source of nutrient inputs to some sites (Bormann et al. 1989).

Stand stemflow as a percentage of total rainfall averaged 1.2% at Smith Island and 0.8% at Diana Lake (Table 3.3). At Smith Island, monthly stemflow ranged from 1.1 to 1.3% of total rainfall, while at Diana Lake, stemflow measured 0.8% of total rainfall. The differences in monthly stemflow are likely due to a number of factors, including canopy state (dry or wet), and rainfall intensity and angle (Crockford and Richardson 2000).

In general, large trees produced a greater amount of stemflow than their proportion of the stand at both sites, with dead trees producing less (Table 3.6). The larger trees have a greater interception area and also extend above the main canopy. The absence of foliage on dead trees means that there is less surface area to intercept rainfall, and thus less stemflow. The results from the smaller tree classes were mixed, making interpretation difficult.

Stemflow represents a small component of forest hydrology, but it plays an important role in directing water to tree roots, and while the added water may not be important in hypermaritime areas, stemflow is often enriched with nutrients from tree canopies and trunks. So although stemflow represents a small percentage of total water input, it has been shown to have a larger effect on the quality of water entering the soil (Johnson 1990).

3.2.5 Results: water balance Water balances were performed for the Smith Island and Diana Lake watersheds between September 1, 1998, and August 31, 2001. Each water balance was performed for a water year (September to August). Results are summarized in Table 3.7. A separate water balance was performed for an additional small watershed in the Diana Lake study area; however, because of the negative residual values for this watershed, the

TABLE 3.6 *Production of stemflow by tree size class*

Tree Class	Smith Island			Diana Lake		
	Sample trees in class	% of trees	% of stemflow	Sample trees in class	% of trees	% of stemflow
DBH < 7.5 cm	3	50	52	4	42	35
DBH 7.5–17.5 cm	2	13	1	3	26	33
DBH > 17.5 cm	8	13	30	5	9	20
Dead trees	4	24	17	3	23	12

TABLE 3.7 *Water balance for the Smith Island and Diana Lake watersheds, 1998–2001*

Location	Precipitation (mm)	Evaporation (mm)	%	Groundwater storage change (mm)	%	Channel discharge depth (mm)	%	Residual[a]	%
Smith Island									
1998–1999	3613	797	22.1	0	0	2433	67.3	383	10.6
1999–2000	3930	805	20.5	0	0	2448	62.3	677	17.2
2000–2001	3650	664	18.2	0	0	2634	72.2	352	9.6
Average	3731	722	19.4	0	0	2505	67.1	504	13.5
Diana Lake									
1998–1999	4110	586	14.3	0	0	3110	75.7	414	10.0
1999–2000	4523	659	14.6	0	0	3604	79.7	260	5.7
2000–2001	4158	602	14.5	0	0	3210	77.2	346	8.3
Average	4264	616	14.4	0	0	3308	77.6	340	8.0

[a] Residual value includes transpiration and measurement error.

results were deemed less reliable and are not presented here. For a complete description of the HyP^3 water balance studies, see Maloney and Bennett (2002).

The Diana Lake study site had a greater orographic effect and, therefore, average precipitation values were higher there (4264 mm) than at Smith Island (3731 mm). Stream discharge accounted for 78% of annual precipitation at Diana Lake and 67% at Smith Island. Evaporation (calculated using forest interception data and forest cover information for each watershed) accounted for 14% (Diana) to 19% (Smith) of precipitation. This left average residual values of 8% at Diana Lake and 14% at Smith Island, a portion of which would be transpiration with the remainder accounted for by measurement error. Maloney and Bennett (2002) outlined various sources of error in hydrology studies, including error estimates of ± 5% for stream discharge values and ± 10–15% for interception values. Winter interception was an additional uncertainty in this study. October interception values were used to estimate winter interception; however, winter interception will depend on highly variable weather conditions, especially the percentage of precipitation falling as snow (Schmidt and Troendle 1992; Pomeroy and Schmidt 1993; Woo et al. 2000). The estimated transpiration for the HyP^3 study watersheds is thus expected to contain a considerable element of error.

Beaudry and Sagar (1995) completed a water balance for a coastal cedar–hemlock ecosystem north of Prince Rupert using a combination of climate and interception measurements and climate modelling. Their study lacked streamflow data, but derived evapotranspiration values through modelling; in contrast, the HyP^3 studies had extensive streamflow data, but lacked detailed estimates of transpiration. For the water balance, Beaudry and Sagar calculated streamflow to represent 75% of total precipitation, with evaporation and transpiration representing 21% and 4% of precipitation, respectively. These streamflow and evaporation estimates, as well as total precipitation (3673 mm), are comparable with the HyP^3 study sites, especially the Smith Island site; therefore, a transpiration estimate of ± 4% may be reasonable for these hypermaritime watersheds.

3.3 Soil Hydrology and Biogeochemistry

How water behaves in the soil has a large influence on the way a site reacts to harvesting-induced changes in hydrology. Soil composition (i.e., whether the soils are dominated by mineral or organic materials) is an important factor in the soil response on the north coast. Ecosystems with soils dominated by organic materials include some zonal scrub forests, as well as bog forests, bog woodlands, and open peatlands. In addition to soil composition, hydrological linkages between forests and wetlands can also affect hydrological responses.

Typically, peat-dominated sites (e.g., bogs) have two main soil layers. The 10–50 cm upper layer contains plant materials, both live and poorly decomposed, including roots and the remains of vascular and non-vascular vegetation. The lower layer is primarily perpetually saturated, well-decomposed organic material (National Wetlands Working Group 1997). The surface layer is the most hydrologically active, with flow rates that may be several orders of magnitude greater than in the lower layer (Ingram 1983). Consequently, when the water table is near or at the surface of the bog, the water is free to move through the more active surface layer (Waddington and Roulet 1997).

Soil pipes are a type of **macropore** that run nearly parallel to the soil surface (Figure 3.8) and are commonly found in many soil types (Uchida et al. 2001). Water flow through pipes is called pipeflow. Pipeflow can be a critical hydrological process that allows the rapid transfer of water to stream channels. Soil pipes are thus important in determining effective **hydraulic conductivity**. Pipes can be disturbed by harvesting activities,

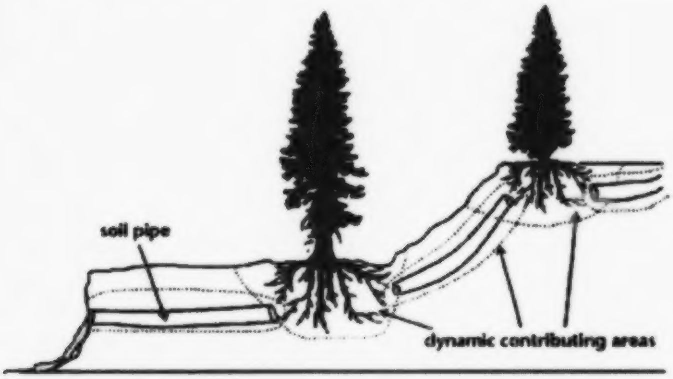

FIGURE 3.8 *Conceptual model of discontinuous soil pipes forming linkages with localized dynamic contributing area.*

potentially changing the drainage patterns of the harvested area.

Soil biogeochemistry, and changes to its dynamics, can also have significant effects on forest management and other resource values. For example, plant productivity is closely tied to nutrient availability, which in turn can be affected by water table height and soil aeration. Both water table height and aeration can be altered by forest harvesting practices.

Carbon cycling is another biogeochemical process that can be affected by harvesting. Carbon cycling in the highly organic soils of the north coast involves the movement of large amounts of dissolved organic carbon (DOC) within the soil profile (Vance and David 1991). Dissolved organic carbon increases water acidity and darkens the water, which gives rise to the naturally tea-coloured water of the area. The dark water, in turn, lowers light penetration, while the increased acidity influences nutrient availability and increases the ability of the water to transport metals (Davies-Colley and Vant 1987; Driscoll et al. 1989; Driscoll et al. 1995). High DOC levels in streamwater also have important implications (both positive and negative) to aquatic biological processes.

3.3.1 Study approach Soil hydrology was studied at both the Diana Lake and Smith Island research sites. Numerous methods were used to determine the hydrological dynamics of the sites. Our methods are presented here briefly; if more detail is required, refer to the source documents (Gibson et al. 2000; Lortie 2002; Fitzgerald et al. 2003; Emili 2003).

Meteorological stations were placed in open bogs at both study sites to measure precipitation. V-notch weirs were set up in several locations in the watersheds to track discharge. Wells and **piezometers** were installed in specific vegetation types throughout the study areas to determine water table depth and hydraulic head. **Time domain reflectrometry** (TDR) probes were used to measure soil moisture content. Automatic recording data-loggers were included at many of these installations.

Hydraulic conductivity was determined using bail tests, and **hydraulic gradients** were calculated using a combination of levelling across the study area and relative water table measurements. Water samples were either collected by hand or with automatic collecting devices; chemical analyses were done in the laboratory.

Natural and artificial tracers were commonly used to determine groundwater flow rates and pathways, and water contributions from different sources (e.g., vegetation types and soil layers). The tracers used included DOC, ratios of the isotopes of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$), salt water, and dyes. In some cases, **hydrograph separation** techniques were then used to determine the quantity of water contributed to streams by different sources before, during, and after rainfall events. Hydrological responses to rainfall events were ascertained using a combination of rainfall data, water table heights, stream discharge volumes and curves, the chemical composition of water, and hydrograph separations.

3.3.2 Results: water tables Depth to the water table was much greater in the upland forest than in the other vegetation types (Table 3.8). The shallowest water table depth occurred in the swamp forest where the water table was often above the ground surface. In most cases, differences in water table depths are closely related to forest productivity. In general, the sites with low water tables are more productive for trees than those where the water table is near the surface, saturating the rooting zone. The swamp forest, however, is an exception—the surface topography allows trees to establish on elevated and better-aerated microsites, and to absorb (some of the) nutrients in the relatively rich mineral seepage of the saturated depressions

TABLE 3.8 *Average depth to water table, pH, and dissolved organic carbon (DOC) of groundwater from mineral and organic soil horizons by site series (adapted from Emili, 2003)*

		pH		DOC (mg/L)	
Site series	Water table depth (cm) (SD)[a]	Organic horizon	Mineral horizon	Organic horizon	Mineral horizon
Upland forest (04)	93.0 (7.1)	n/a	6.03	n/a	8.2
Scrub forest (01)	22.2 (7.6)	5.04	5.52	17.6	11.1
Bog forest (11)	14.3 (6.5)	n/a	5.19	12.6[b]	7.5[b]
Bog woodland (12)	15.3 (5.0)	4.89	5.44		
Open peatland (32)	7.9 (6.9)	4.85	5.62	16.6	10.2
Swamp forest (13)	3.2 (5.4)	n/a	n/a	n/a	n/a

a Standard deviation.

b DOC data combined for the bog forest and woodland vegetation types.

(Banner et al. 1993). The physical amount of water table fluctuation, as indicated by the standard deviation, was similar at all sites. At sites with high water tables, however, the water table is often very close to the surface where the saturated conditions affect tree growth.

3.3.3 Results: soil hydrological dynamics

The hydrological dynamics of the outer north coast depend on several interacting factors. Ground surface slope, as shown by a slope index (that combines slope angle and slope length), influences drainage rate and, therefore, water table height and soil moisture content (Emili 2003). Lower slopes and depressions are wetter and tend to accumulate organic matter in the form of peaty soils. This relationship is quantified by the slope index that, in turn, is related to vegetation type and organic soil depth (Emili 2003). These findings correspond with those of Asada (2002), who found that vegetation types were most influenced by water table depth and slope.

Peaty soils, in a positive feedback loop, profoundly influence soil drainage characteristics. These organic soils have a low hydraulic conductivity, which decreases water infiltration rates and groundwater flow, and restricts soil water discharge (Emili 2003). The soils also have a high water retention capacity, which enables them to retain pore water for long periods, and thus remain saturated. Wet soil conditions facilitate the accumulation of organic matter, restrict tree growth, and favour the establishment of wetland species, such as sphagnum mosses and sedges.

The low hydraulic conductivity of the organic soil matrix encourages alternative subsurface pathways (e.g., pipes and macropores) to develop, which are critical in removing water from these sites. Often short (5–10 m) and terminating in seeps and rills, these pathways permit more rapid water movement than the regular soil matrix flow (Gibson et al. 2000). The low hydraulic conductivity of organic soils also results in surface flow during storm events.

Hydraulic conductivity is also an important factor in the variation of water residence times in organic and mineral soil-based terrain types. In organic soils, low hydraulic conductivity results in soil water retention and, therefore, little unused storage capacity is available to absorb water from the next rainfall event. This forces new water to leave organic soils quickly. As a result, streams in organic soil terrain types are less stable (i.e, "flashier") than those in mineral soil terrain types (Gibson et al. 2000). In addition, runoff patterns are influenced by the weather conditions preceding a storm event.

Hydrological dynamics differ with rainfall intensity and between the soil surface and subsurface layers. These differences are attributed, in part, to the presence of peat, which maintains a shallow water table (Gibson et al. 2000). In the scrub forest, the shallow groundwater system responds rapidly to rainfall events, as indicated by a rapid rise in water table and DOC concentrations in the shallow groundwater and streams during rainfall events, but not in the deep groundwater. A shallow water table keeps most of the inputs of water in the near-surface groundwater zone, and much exchange occurs with the surface as groundwater seeps. Incoming water moves through the upper soil layers, exits the soil from numerous groundwater seeps, and flows over the ground surface before reaching the stream. Conversely, the deep groundwater system shows little reaction to rainfall events (Gibson et al. 2000; Lortie 2002). The deep groundwater zone only receives a small proportion of the new water inputs, especially in the bogs, because of the low hydraulic conductivity of deeper organic horizons, and the relatively few macropores in the deeper soil horizons (Gibson et al. 2000; Lortie 2002).

At low rainfall intensities, a "first-in-first-out" hydrological dynamic generally exists, where old water is pushed out of the system using internal soil flow pathways. At high rainfall intensities, the flow capacities of these pathways are exceeded and alternative pathways involving rapid flow (i.e., rill and seep flow) are invoked. This results in a "last-in-first-out" hydrological dynamic, where streamflow is dominated by new water (Gibson et al. 2000) that usually travels through shallow groundwater pathways before reaching the stream (Figure 3.9). After rainfall events, deep groundwater resumes its role as the major contributor to streamflow. The rainfall threshold at which the flow-pattern change occurs is not known, but is likely lower after harvesting because of the decreased rainfall interception by the canopy.

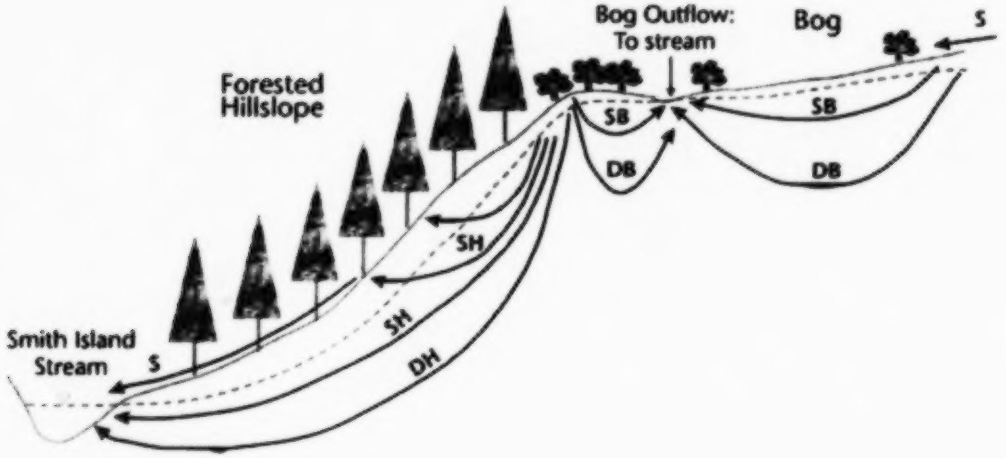

FIGURE 3.9 *Model of groundwater flowpaths in zonal forests and open bogs in the Smith Island watershed. Dashed line is the water level beneath the ground surface and in the stream. Solid lines represent the groundwater flowpaths: SH = shallow hillslope flowpaths; DH = deep hillslope flowpaths; SB = shallow bog flowpaths; DB = deep bog flowpaths; S = groundwater seep.*

3.3.4 Results: pipeflow studies In north coast lowland forests, four main factors appear to facilitate the development of soil pipes:

1. presence of a soil discontinuity with depth (i.e., a highly conductive surface organic layer [1–55 m/day] overlies a low-conductivity [0.0004–0.002 m/day] peat);
2. steep hydraulic gradients;
3. organic soils with low cohesion; and
4. high volume of living roots and buried coarse organic material.

In this setting, pipes may form by a subsurface flow through the surface organic layer, which cuts into the underlying, more decomposed organic soil. With little solid soil structure to hold it in place, this organic soil is often eroded, allowing pipe formation. Pipes were found throughout soil profiles at the study sites, but were most abundant at structural voids and roots (i.e., at the junction between high- and lower-conductivity soil horizons), at the soil–root interface (Figure 3.10a), along conduits of decayed roots, and along the soil–bedrock interface (Figure 3.10b).

Excavation revealed that channelled sections of pipes were continuous over short distances (5–10 m). Water tracing with salt water and dye, however, showed that hydraulically effective and connected flow paths occurred over much longer distances, likely through linkages at nodes. These nodes can be tree root masses, areas with more highly hydraulically conductive soil, deadfalls, or zones where **overland flow** occurs.

During a storm, the size of an area contributing to direct runoff expands and contracts according to a theory known as the "variable source area concept" (Dunne and Black 1970). This area is calculated using the following formula (Jones 1997):

$$\text{Area} = \frac{\text{Total storm discharge in pipe or stream (m}^3\text{)}}{\text{Total storm rainfall (m)}}$$

This formula uses the amount of water discharged during an event and the amount of rainfall that fell during an event to determine the area that contributed to discharge.

The area that contributes water to a pipe during storms may be enlarged by a

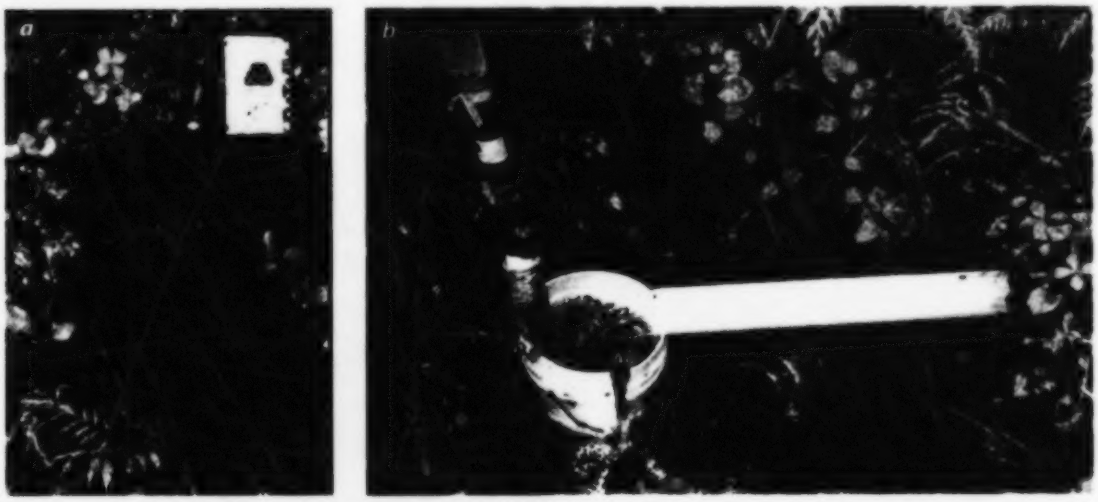

FIGURE 3.10 *Examples of soil pipes: (a) excavated soil pipes formed around live roots located in a cedar–hemlock forest; (b) soil pipeflow directed into a bucket weir for measurement of discharge.*

rising water table, overland flow from perched saturated zones, or groundwater which discharges at the surface and flows into pipe channels. This drainage system is similar to the discontinuous macropores on forested hillslopes in Japan described by Sidle et al. (2001), although the north coast of British Columbia has a much wetter hydrological regime.

Two basins were chosen for monitoring, each with different physical characteristics (Table 3.9). These basins were chosen for their small size, which facilitated the integration of climate–soil–vegetation dynamics, their proximity to pre-existing monitoring areas, and their contrasting drainage systems. The larger of the two basins, the "S01 basin," is dominated by a small **first-order stream**, which originates near the toe of a scrub forest slope at the margin of a bog containing an abundance of buried deadfall. The stream meanders for about 30 m before discharging into "Smith small stream." Runoff from the second basin, the "K-pipe basin," is dominated by a 10–20 cm diameter soil pipe that is 30–50 cm below the surface at the organic–mineral and mineral–bedrock interfaces. The K-pipe basin was traced visually over 7 m from its discharge point through a wave-cut terrace on the beach at Inverness Passage (Figure 3.10b). Live and dead tree root masses and areas of ponded water occurred at irregular intervals along this pipe. Beyond 7 m, surface evidence of the pipe vanished into a thick (> 1.5 m) deposit of peat. Along a 100 m section of the wave-cut terrace, eight smaller soil pipes were noted. With the exception of one other perennial pipe, all of these flowed ephemerally.

Though similar CWHvh2/01 forests dominate both basins, notable differences are apparent in soil characteristics and topography (Table 3.9). Soil depth at the S01 basin averaged 0.6 m on hillslopes, greater than 1.5 m in mid-slope boggy benches, and greater than 3 m in the bog forest. Soil depth at the K-pipe basin was seldom greater than 1.2 m, with hydraulic conductivity averaging three orders of magnitude greater than the S01 basin. Here, the zone of highest conductivity roughly coincided with the suspected depth of the pipe channel.

Surface water storage exerts a greater influence over the K-pipe basin than the S01 basin; swampy areas of standing water cover approximately 20% of the K-pipe basin. During storms, these areas expand to form a network of pools linked by areas of return flow. Presumably, this is the

TABLE 3.9 *Characteristics of the S01 and K-pipe basins*

	S01 basin	K-pipe basin
Basin area (m^2)	7331	2763
Drainage	first-order stream	Perennial soil pipe
Slope	8–38°	5–10°
Soil thickness (m)	0.1 to > 3	0.5–1.5
Hydraulic conductivity (m/d)	0.00038–0.13 average = .024	2–51 average = 25
Dominant vegetation	Approx. 50% moderately sloping scrub forest: western redcedar, yellow-cedar and hemlock; and approx. 50% gently sloping bog forest, scattered areas with standing water.	Gently sloping scrub forest: western redcedar, yellow-cedar and hemlock, with interspersed swamp forest and abundant surface pools.
Dominant site series	70% 01 scrub forest 30% 11 bog forest	70% 01 scrub forest 30% 13 swamp forest

surface expression of pipe channel flow under pressure, as the pipe channel varies its course both vertically and horizontally within the soil profile (Woo and Dicenzo 1988). In contrast, the S01 basin has much smaller isolated pools of standing water that are restricted to riparian zones at the base of the CWHvh2/01 hillslope and at scattered sites throughout the bog forest.

The typical stormflow and groundwater response (Figure 3.11) to a well-defined, single-peak storm event was rapid from both the K-pipe and S01 basins, with similar peak rainfall to peak discharge times for each. The response time (measured as the difference between the start of rainfall and initial increase in discharge) for the K-pipe basin, however, was about twice as rapid (average of 2 hours). Even when the antecedent groundwater level in both basins was similar, the threshold groundwater level required to initiate stormflow differed. In the S01 basin, an increase in stream discharge coincided with a water table rise to within 5–10 cm of the surface. In the K-pipe basin, pipe discharge started to appreciably increase when the water table rose above the base of the pipe channel, which was about 30 cm below the ground surface. **Baseflow** separation revealed consistently higher contributions of baseflow to the K-pipe basin (16–44%) compared with the S01 basin (10–34%).

The S01 basin receded much faster than the K-pipe after storms, exhibiting progressively steeper recessions with decreasing discharge (Figure 3.12a and 3.12b). The abrupt recession observed in the S01 basin is explained by smaller contributions from baseflow, rapid disconnection from the bog forest and hillslope source areas, the lack of dynamic storage in the stream channel, and seepage losses to the gravel streambed and surrounding soil. Conversely, the extended recessions observed in the K-pipe basin imply a more intimate contact with the water table, and greater post-peak contribution from swampy surface depressions draining through surface macropores and higher-conductivity soils.

The dynamic contributing areas (DCA) for the S01 and K-pipe basins were compared with measures of basin wetness to determine the controls on runoff (Figure 3.13). The S01 basin's DCA is generally well predicted by the following measures of basin wetness:

- antecedent water level ($r^2 = 0.70–0.95$);
- 1-day antecedent soil moisture ($r^2 = 0.48–0.75$); and
- 5- and 10-day antecedent precipitation ($r^2 = 0.63–0.75$).

The K-pipe basin DCAs had somewhat different relationships with measures of basin wetness. The DCAs grew with increasing antecedent precipitation to about 20 mm. Between 20 and 50 mm 10-day antecedent precipitation, contributing areas began to shrink. Contributing area had an inverse relationship with the following precipitation indices: magnitude, intensity, rainfall depth before **peak flow**, and storm duration. The apparent shrinking of DCAs as the catchment becomes wetter is explained by the activation of ephemeral soil pipes under very wet conditions. With increasing catchment wetness, these pipes serve to divert stormflow away from the K-pipe basin, which results in a smaller apparent contributing area. This was corroborated by the pipeflow tracer experiments, which established connections between the K-pipe basin and a number of neighbouring ephemeral pipes.

Compared with the S01 basin, the K-pipe basin experienced a more rapid response to precipitation and more gradual recessions because of its intimate contact with the water table, higher-conductivity soils, and affiliation with a network of smaller ephemeral pipes and nodes. Another factor involved in the rapid response of the K-pipe basin, and expansion of the contributing area during a storm, is its large area of swamp forest with significant surface depression storage. Swamp forests can have a large proportion

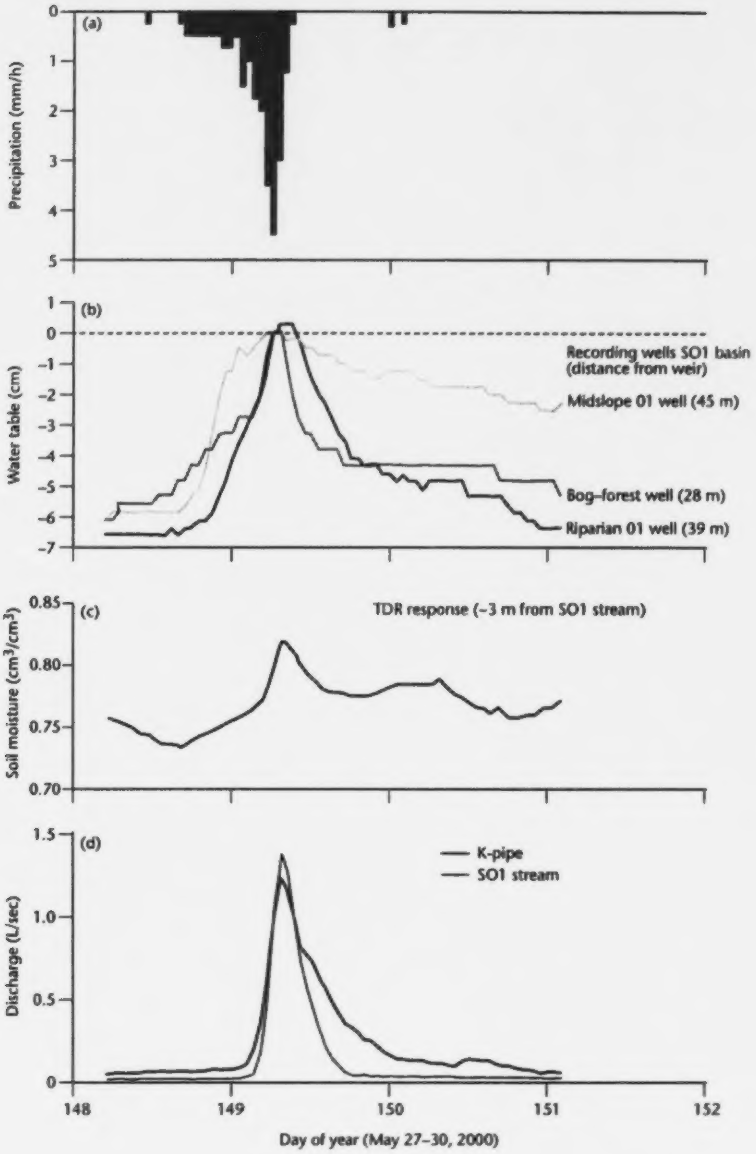

FIGURE 3.11 *Comparison of typical storm hydrograph response between the K-pipe and S01 basins: (a) precipitation during event; (b) water table depth at three locations; (c) soil moisture response in S01 basin; (d) discharge profile from the K-pipe and S01 basins.*

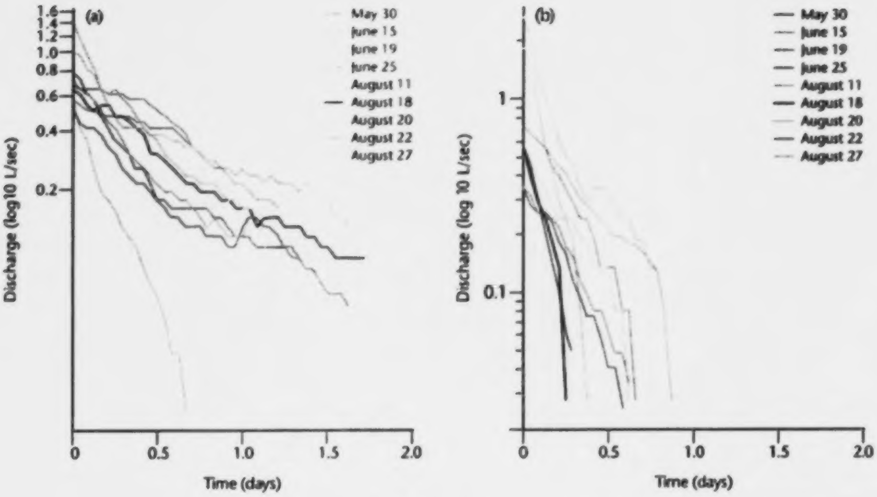

FIGURE 3.12 *Selected storm recession graphs for the (a) K-pipe and (b) S01 basins during the 2000 field season.*

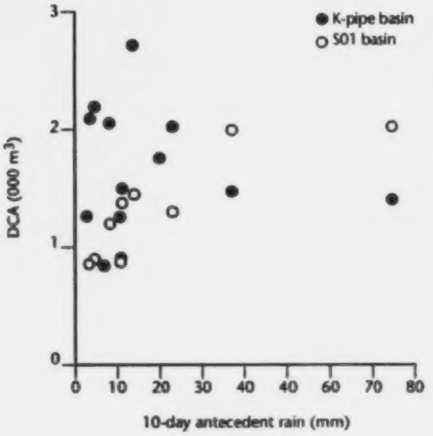

FIGURE 3.13 *Relationship between the S01 basin and K-pipe basin dynamic contributing areas (DCA) and 10-day antecedent rain.*

of a basin's water routed through them, causing discharge to increase rapidly when storage capacity is exceeded (Fitzgerald et al. 2003). In the S01 basin, streamflow is fed primarily by shallow subsurface flow through the near surface peat and by overland flow as the water table intersects the ground surface. Consequently, the S01 basin becomes rapidly disconnected from source areas as the water table declines. Because the S01 basin has much steeper slopes and contains only a minimal area of swamp forest, overland flow and **preferential flow** are common, but largely restricted to discrete areas of the basin.

3.3.5 Results: hydrological landscape linkages The mosaic of vegetation types typical of the north coast suggests that hydrological linkages between site series are common; therefore, forest management actions may have hydrological effects that extend beyond the boundary of the harvested forest type. Some forest types may have a larger controlling influence on watershed hydrological dynamics than others. This section summarizes the results of an investigation of hydrological linkages among several site series within the Diana Lake study area.

Bog isolation By definition, bogs are peatlands that receive water input exclusively from direct precipitation (National Wetlands Working Group 1997).

Consequently, bogs are usually considered to have no groundwater and surface water inputs from the surrounding landscape. Some evidence, however, suggests that this isolation is less absolute than previously thought (Siegel et al. 1995). Establishing this hydrological autonomy is essential to understand the implications of disturbances in the forests adjacent to wetland ecosystems. For example, if bogs are hydrologically isolated, and no harvesting-related activities occur directly on the bog surface, then activities on slopes above or below the bog may not greatly affect the hydrology of the bog itself. To further examine this issue, we attempted to characterize the nature and strength of the hydrological linkage between a bog that has developed within a complex landscape, and the adjacent forests, specifically the CWHvh2/04 and /01 site series at the Diana Lake study site.

Water budgets for two rainfall events (July 22 and 28, 1999) were used to determine whether the bog experienced any water inputs or exports. During the first rainfall event, 17 mm of rain fell in 20 hours, and during the second event, 56 mm fell in 47 hours (Figure 3.14a). Using the water budget equation (see section 3.2.1), we calculated that 121 m^3 of rain fell on the bog during the first event. Of this amount, 106 m^3 was taken up in groundwater storage and 13 m^3 was discharged over the stream weir, which accounted for 119 m^3 of the 121 m^3 input (Figures 3.14b and 3.14c). Evapotranspiration over the duration of the storm event was likely negligible and, therefore, ignored. For the second event, we calculated that 400 m^3 of rain fell. Of this amount, 350 m^3 was discharged, 9 m^3 was stored as groundwater, and 41 m^3 was stored in surface pools that covered about 10% of the catchment area.

The full accounting of the input, storage, and discharge from two storms, one of which followed a dry period, the other a wetter period, demonstrates the hydrological independence of this bog system from adjacent ecosystems. During the first event, most of the rainfall was accounted for by the change in water storage within the bog—almost no water was lost by surface drainage through the stream. For the

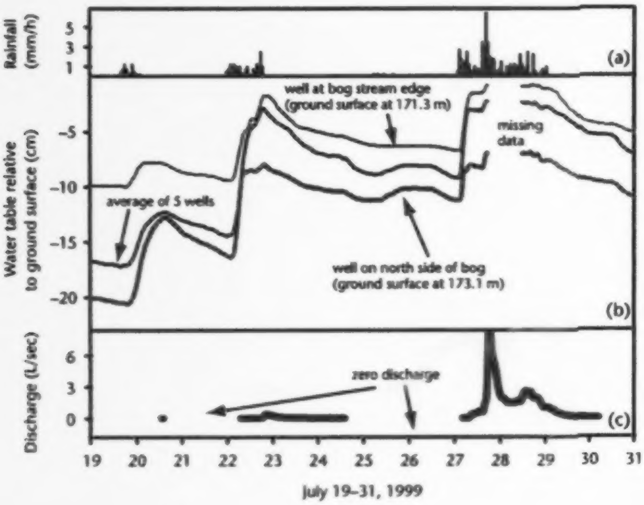

FIGURE 3.14 *Hydrological parameters measured in a bog at the Diana Lake study site: (a) precipitation; (b) bog water table elevation relative to ground surface; and (c) discharge recorded at the bog weir.*

second event, inputs were primarily accounted for by discharge and storage change (i.e., water table rise).

Despite the macro-scale topographic connection between the bog and the adjacent forested slope, no apparent hydrological linkage exists between them as seen by the lack of water inputs from these areas. This lack of water transfer between the forest and bog is due to subtle differences in elevation and flow paths at the margins of these two systems. Seepage losses at the foot of the forested CWHvh2/04 slope (Fitzgerald et al. 2003) are intercepted by a seepage channel that skirts the perimeter of the bog on its northern side. Thus, if forestry activities occurred on the slopes above this bog, the bog's hydrological budget and its ecological integrity would be largely unaffected. The bog would incur little environmental damage, as long as machinery did not traverse the bog, including the bog margins. This bog, however, does not represent all peatlands on the outer coast because this landscape produces wetlands in many different topographical and hydrological settings. Each specific situation must be properly interpreted before concluding that adjacent ecosystems are hydrologically isolated.

Swamp forest and hillslope interactions

Swamp forests (Western redcedar – Sitka spruce – Skunk cabbage; CWHvh2/13 site series) are localized in water-receiving areas such as lower slopes and depressions. Although relatively common in the CWHvh2, these forests generally do not cover extensive areas. Swamp forests were recognized as being hydrologically connected to other forest types, but the strength of this linkage was not known. A study carried out at Diana Lake was designed to investigate the relationship between swamp forests and the adjacent forests that provide water to them, in this case, an upland productive forest (CWHvh2/04).

This study showed that the swamp forest was fed by both ground and surface water from the upland productive forest. During rainfall events, up to 95% of the water in the stream was routed through the swamp forest, though it only occupied 25% of the catchment area (Fitzgerald et al. 2003). This water was held in the swamp forest before its release to the stream. Between rainfall events, the proportion of water in the stream coming from the swamp forest steadily declined as the water table dropped.

The upland productive forest also discharged water into the stream via seeps. The discharge in these seeps was not sensitive to variation in the water table height in the upland productive forest. The discharge from the swamp forest, however, was sensitive to water table changes. This indicates that harvesting activities on the upland productive forest will have less of an effect on stream hydrology than harvesting of the swamp forest (Fitzgerald et al. 2003). If these swamp forests are harvested, the water table could rise (Dubé et al. 1995), decreasing available water storage capacity, increasing peak water flows, and potentially increasing the risk of flooding (Fitzgerald et al. 2003). Our preliminary results suggest that harvesting of swamp forests should be avoided because of potentially negative on-site and off-site hydrological impacts. In the specific situation at this study site, hydrological linkages exist between the hillslope productive forest and the swamp forest. Therefore, removal of the canopy on the hillslope forest and the resulting interception and evaporative losses would have some influence on the swamp forest below and indirectly affect stream flows.

3.3.6 Results: soil water chemistry Mean groundwater pH for all forest types combined was lower in the organic horizons than in the mineral horizons (Table 3.8). The differences in soil water pH between horizons is likely due to the acidic nature of coniferous forest litter, the acidifying abilities of sphagnum and other mosses in the organic layer, and the higher pH of the mineral soil itself. In the mineral horizon, soil water pH was highest in the upland forest and lowest in the bog forest, though the differences were not statistically significant.

Vegetation type and soil type were important factors in the ionic makeup of groundwater; slope, water table depth, and groundwater flow were not significant factors for any of the ions measured. Productive forests (CWHvh2/04) had significantly higher concentrations of bicarbonate (HCO_3), sulphate (SO_4), calcium (Ca), magnesium (Mg), and sodium (Na) than the lower-productivity scrub forest, bog forest, bog woodland, and open bog vegetation types (CWHvh2/01, /11, /12, and /32, respectively), while potassium (K) was higher in the forested communities (CWHvh2/01, /04, and /11) than the peatland communities (CWHvh2/12 and /32) (Table 3.10) (Emili 2003). Groundwater from mineral soils tended to have higher concentrations of nutrients than that from organic soils (Table 3.11), though the differences were not statistically significant. This indicates that groundwater contact with mineral soils accounts for the higher concentration of nutrients in the forested vegetation types where organic horizons are shallower. Many ions also tended to have higher concentrations in the summer than in other seasons (Table 3.12). At Diana Lake, nitrate (NO_3),

TABLE 3.10 *Mean[a] ionic composition of groundwater (mg/L) by site series at Diana Lake, 1997–1998 (adapted from Emili, 2003)*

Site series	HCO_3^-	Cl^-	NO_3^-	NO_2^-	PO_4^-	SO_4^-	Ca^+	Mg^+	Na^+	K^+	Fe^+	Mn^+	Al^+	Zn^+
Scrub forest (01)	10.5b	2.1	0.05	0.01	0.02	2.9b	1.5b	0.3b	2.6b	1.0b	0.6	0.03	0.4	0.2
Bog forest (11)	9.0b	2.5	0.04	0.01	0.01	< 1.04[b]	1.5b	0.9b	2.3b	1.2b	0.8	0.05	0.3	0.2
Bog woodland (12)	13.7b	1.6	< 0.02	0.01	0.01	< 1.04	2.7b	0.3b	1.9b	0.5a	0.9	0.01	0.1	0.3
Open peatland (32)	27.8b	1.5	< 0.02	0.01	0.02	1.9[c]	3.8b	0.5b	2.3b	0.6a	1.1	0.02	0.1	0.5
Upland forest (04)	35.0a	3.2	0.12	0.03	0.03	3.6a	10.2a	1.2a	3.2a	1.1b	0.0	0.03	0.1	0.0

a Means within a column followed by a different letter are significantly different ($p < 0.05$), $n = 153$.

b "<" indicates concentration below specified detection limit

c One sample above detection limit.

TABLE 3.11 *Mean ionic composition of groundwater (mg/L) in the organic and mineral subsoil horizons at Diana Lake, 1997–1998 (adapted from Emili, 2003)*

Soil type	HCO_3^-	Cl^-	NO_3^-	NO_2^-	PO_4^-	SO_4^-	Ca^+	Mg^+	Na^+	K^+	Fe^+	Mn^+	Al^+	Zn^+
Organic horizon	13.4	2.2	0.04[a]	0.02	0.02	1.9[a]	2.0	0.3	3.5	1.1	0.7	0.02	0.2	0.2
Mineral subsoil	16.0	2.1	0.07	0.02	0.02	3.3	2.6	0.4	3.8	0.8	0.6	0.03	0.3	0.3

a One sample above detection limit ($n = 153$).

TABLE 3.12 *Mean[a] seasonal ionic composition of groundwater (mg/L) at Diana Lake, 1997–1998 (adapted from Emili, 2003)*

Season	HCO_3^-	Cl^-	NO_3^-	NO_2^-	PO_4^-	SO_4^-	Ca^+	Mg^+	Na^+	K^+	Fe^+	Mn^+	Al^+	Zn^+
Summer	20.7b	2.5b	0.12	0.01	0.02	2.3	2.9	0.6	3.6	0.9	1.6b	0.03	0.5b	0.9a
Fall	–	1.5ab	< 0.02[b]	0.01	0.02	3.4	3.3	0.4	1.3	0.7	0.5a	0.03	0.2ab	0.1b
Winter	12.1a	3.2a	0.4	0.01	0.01	< 1.04	1.3	0.2	2.9	0.9	0.4a	0.03	0.1a	0.2ab
Spring	6.2b	1.4ab	0.5	0.01	0.01	3.7	1.3	0.3	2.7	1.3	0.2ab	0.02	0.2ab	0.1b

a Means within a column followed by a different letter are significantly different ($p < 0.05$; $n = 153$).

b "<" indicates concentration below specified detection limit.

sulphate, and phosphate (PO_4) concentrations were very low in the vegetation types where the water table was high and reducing conditions were present (Emili 2003).

Dissolved organic carbon concentrations differed with vegetation type (Table 3.8), season, and soil type. Dissolved organic carbon was higher in the swamp forest and open peatland than in the bog forest, bog woodland, and upland forest, each having progressively lower values (Emili 2003). This pattern was likely due in part to the relative thickness of the organic horizon in the various vegetation types. Dissolved organic carbon was highest in summer, which is likely linked to increases in microbial activity when temperatures are warmer and rainfall is less (i.e., less dilution). The DOC was also highest in shallow groundwater, with much lower values in the deep groundwater (Figure 3.15) (Gibson et al. 2000; Lortie 2002; Emili 2003). This pattern results from the production of significant amounts of DOC in the organic-rich surficial deposits, and less in the underlying mineral soils (Schiff et al. 1990). In addition, water that moves to deeper mineral layers loses some of its DOC by decomposition and absorption as it filters down through the soil. The positive relationship between DOC and discharge indicates that, during rainfall events, DOC is flushed from the groundwater system to the stream.

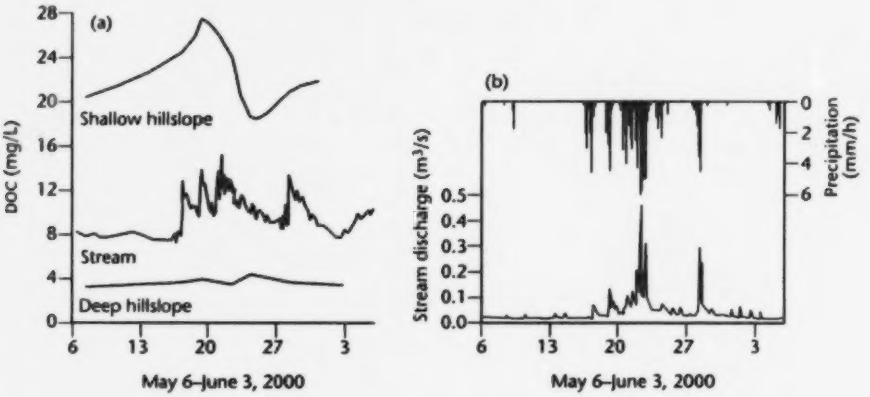

FIGURE 3.15 *Dissolved organic carbon (DOC) concentrations, rainfall, and stream discharge, Smith Island watershed: (a) stream, shallow hillslope, and deep hillslope DOC response to rainfall events; (b) rainfall and stream discharge response during the rainfall event.*

3.4 Discussion and Summary

3.4.1 Watershed hydrology and canopy interception Rainfall event size and a watershed's preceding moisture condition, especially its soil water storage capacity, control hydrological response and lag time. Rainfall events must first fill the available soil water storage capacity before producing a hydrological response. The storage capacity is greater after a dry period than after a wet period. A small event preceded by a wet period produces a larger hydrological response and a shorter lag time because of the smaller amount of available soil water storage capacity. Large rainfall events can produce larger hydrological responses because a greater proportion of the event's water is surplus to available storage capacity and is discharged.

Lag times for large rainfall events closely match those for small events with corresponding preceding conditions, as soil water storage capacity is not controlled by the size of the event but by transpiration, evaporation, and discharge. The longer lag times after dry periods are a result of the increased storage capacity, and produce a delayed hydrological response.

Hypermaritime watersheds such as those found in the CWHvh2 have a relatively small amount of water storage capacity. The shallow, dominantly organic soils typical of these watersheds have high water retention capacity, and are frequently saturated in this wet climate. The small amount of available water storage capacity in these soils means that significant runoff is generated from relatively small storms. A dense network of soil macropores and pipes rapidly route the excess water downslope to stream channels.

Compared with other locations, rainfall events in the CWHvh2 produce a larger hydrological response. Both the average hydrological response of 0.41 and the largest response of 0.81 are high compared with the weighted average of 0.20 recorded for streams in the eastern United States, where the highest response was between 0.40 and 0.50 (Hewlett 1982). In contrast, hydrological response values of 0.55 (Cheng 1988) and greater than 0.90 (Hetherington 1987) were recorded for individual rainfall events in British Columbia, and a value of 0.63 was recorded following a wet period in Barrow, Alaska (Dingman 2002). In the United States studies, the 0.40 and 0.50 response values were found in locations with shallow soils and steep slopes (Dingman 2002), whereas the values recorded here were on gentle terrain with mainly organic soils. The high response on shallow slopes indicates that the system has little storage capacity and rapid water transfer mechanisms.

Most rainfall and runoff information for the forested watersheds along the north coast of British Columbia is based on data collected at the Prince Rupert Airport, which is located near sea level. Rainfall data collected for this study, however, indicates that 27% more rainfall occurs at higher elevations (337 m).

About 55% of annual rainfall at the Diana Lake 72-m site resulted from events larger than 40 mm, and 19% from events 100 mm or larger, which indicates events producing large hydrological responses occur regularly. This has important implications both for harvesting and road and drainage structure construction. The current precipitation shutdown guidelines assume a daily drainage rate of 55 mm/day, and require a positive water balance of 100 mm before shutdown. Precipitation-based operational shutdown guidelines for the north coast are currently under review (agra Earth and Environmental 1996; Price 2002); any new guidelines should recognize the influence of orographic rainfall in the mountainous watersheds of the region by ensuring that rainfall is measured locally.

Topography, wind direction, and the spatial variability of rainfall events all contribute to the rainfall patterns found in the Smith Island and Diana Lake watersheds. At Smith Island, the lower barriers surrounding the monitoring sites are likely responsible for the smaller orographic effect. In addition, the southern part of the island has higher elevations than the northern part where the monitoring sites are located. Consequently, moist southern air masses possibly lose some of their moisture before reaching the monitoring sites on the north side of the island. The relationship between rainfall and elevation is not always linear, however, and can be influenced by local topography over short distances. For example, although both are at the same elevation, more rainfall is recorded at the Diana Lake mid-slope site compared with the hilltop site. This rainfall pattern may be produced as airflow accelerates over a barrier with a steep, narrow upwind face, which results in more rainfall on the leeward side of a mountain than on its hilltop (Daley et al. 1994).

We did not conduct a detailed examination of the contributions of cloudwater and fog drip as hydrological and nutrient inputs (see Emili [2004] for details of rainfall, throughfall, and fog drip inputs and chemistry). Our sampling approach did not permit the separation of simultaneous occurrences of fog drip from drizzle; however, other studies have shown that these sources of "occult precipitation" represent significant inputs to coastal forests (e.g., Bormann et al. 1989; Harr 1982) and, therefore, this topic warrants more detailed study on the north coast.

The decrease in canopy interception after harvesting increases the amount of water received on the ground. At the two study sites, the canopy intercepted 20–25% of the average annual rainfall (i.e., for the May to November ice- and snow-free study period). If the areas are clearcut, the amount of water that must be removed by existing hydrological processes can be expected to increase. A similar study found that interception after harvesting decreased by two-thirds when measured under the shrub layer (Roy et al. 2000); our measurements, however, were made above the shrub layer. The possible hydrological consequences of this decreased interception include:

- a decrease in time to peak flows after a storm;
- an increase in peak flow volumes;
- an increase in water table height; and
- an increase in erosion, as natural drainage pipes reach capacity sooner and more overland flow occurs.

Although increased erosion of organic soils (especially if the soil surface is disturbed) is possible due to their high water retention and low cohesion qualities, the relatively gentle slopes on which these low-productivity forests occur will experience lower surface water runoff velocities, and thus lower off-site sediment transport, than steeper hillslopes. Higher peak flows in streams are also possible, which may increase the risk of erosion and flooding (Lortie 2002). In small watersheds, however, the risk of greatly increased peak flows is low (Beschta et al. 2000).

The introduction of additional water to a drainage system can be managed using the current watershed assessment procedures for road building and bridge engineering. By knowing the harvested area and the watershed's discharge characteristics, the increase in peak flows can be identified and managed.

In eastern Canada, the increase in water on forested sites after harvesting is influenced more by interception than by transpiration (Dubé et al. 1995). Preliminary estimates of transpiration from the water balance studies of Maloney and Bennett (2002) and Beaudry and Sagar (1995) suggest that this is also the case in west coast hypermaritime ecosystems. Modified harvesting regimes will help to minimize the decrease in rainfall interception. Following regeneration of the harvested area, canopy interception begins to increase again as trees grow.

3.4.2 Hydrological dynamics and linkages

Hydrological dynamics differ among forest types. Our study shows that swamp forests (CWHvh2/13) receive much of their water input from other forest types, and are important in mediating discharge flows, whereas upland productive forests (CWHvh2/04) have deeper water tables and mainly export water. Swamp forests, therefore, are more sensitive to harvesting-induced hydrological changes than upland productive forests; they should not be harvested because of their importance in receiving water and regulating streamflow within a watershed, and their potential for increased water tables. Upland productive forests are much less sensitive in these respects and could be harvested with fewer on-site hydrological impacts. Off-site impacts to adjacent swamp forests, or other hydrologically sensitive ecosystems, are still a potential concern wherever direct linkages occur. Upland scrub forests (CWHvh2/01) will likely have an intermediate response, with water tables rising slightly depending on specific site and soil characteristics. These scrub forests and their potential timber values are currently of interest; therefore, future operational trials should monitor and quantify any hydrological impacts. Some limited data on water table fluctuations associated with harvesting scrub forests are available from the Port Simpson study site (Beaudry et al. 1994). The effects are quite variable and apparently related to local soil and topographic conditions, as well as the location of skid roads that act as local drainage pathways. Although there was no significant difference between average water table heights before and after harvesting, in the wells located adjacent to skid trails, water tables tended to drop; in the wells located away from the skid trails, water tables tended to rise. At the Oona River operational trial, although changes in water tables were not measured, the relatively small areas of flat and low-lying portions of the blocks were observed to have some surface ponding after harvest that was not apparent pre-harvest.

A rise in water table could be an important ecological problem if scrub forests are harvested. Smaller rainfall events would saturate these forest soils because of the reduced interception and transpiration following canopy removal (Maloney et al. 2002; Dubé et al. 1995). A rise in water tables, or "watering up," occurs in other forested wetland areas following harvesting, especially on transitional sites between wetlands and uplands where the water table is deeper than in the true wetlands (Dubé et al. 1995). Rises in the water table will vary by forest type and slope position. Higher water tables result in less storage capacity in the soils, a shallower **aerobic** rooting zone, a greater number of groundwater seeps, and altered nutrient dynamics. Higher water tables also hamper regeneration and promote paludification (Asada 2002).

Regeneration success can be improved by site preparation that includes soil mixing and mounding (Shaw and Banner 2001a, 2001b); however, care must be taken to avoid creating the conditions (e.g., pools beside mounds) that facilitate sphagnum moss growth and paludification (Asada et al. 2002). If forest regeneration is successful, canopy interception will increase again as trees grow. In fast-growing New Zealand pine plantations, runoff parameters (e.g., peak flows, **quick flows**, and low flows) returned to pre-harvest levels 10 years after replanting (Fahey and Jackson 1997). The rate of canopy development in harvested scrub forests of coastal British Columbia is expected to be considerably slower, however.

In a study of peak streamflows in relation to forest harvesting on eastern Vancouver Island, Hudson (2002) used the concept of equivalent clearcut area (ECA) that accounts for hydrological recovery due to forest regeneration. He found that the mean response to a decrease in ECA of 10% (as sites regenerated) was a decrease in peak flow of 40–50%.

Forestry activities adjacent to wetlands involve possible hydrological effects, ranging from the complete cut-off of water inputs to the wetland to a considerable increase in water inputs. The magnitude of these effects will depend on the degree to which the wetlands are hydrologically isolated. Decreases in water inputs could result from constructing logging roads on slopes that feed wetlands; increases in water inputs (e.g., from the streams that feed wetlands) could result from removing the adjacent forest canopy. At both extremes, these activities may initiate changes in hydrology that could affect wetland functioning and species composition. To avoid any negative effects, it will be necessary to assess whether the extensive bog and other wetland ecosystems typical of the CWHvh2 landscape are hydrologically connected to areas planned for harvest. Reconnaissance-level topographical and stream channel surveys are effective procedures in such assessments.

3.4.3 Soil pipes Our study results show that soil pipes play an important role in draining forests in the hypermaritime north coast. The two contrasting study sub-catchments had different water transport mechanisms, and harvesting will affect each differently. With its gentler slopes, the K-pipe basin will likely experience a greater water table rise, and soil pipes will be most important in water transfer from the site.

Soil pipes transport stormflow rapidly and efficiently; however, if harvesting damages these pipes, they could become "short-circuited," decreasing their capacity to route stormflow through the landscape. Harvesting also reduces canopy interception, which may result in greater soil water inputs and thus more overland flow, higher peak discharge rates, and shorter lag times (Ziemer 1992; Keppeler and Brown 1998).

Soil pipes can contribute to soil stability in two ways:

1. by increasing the rate of soil drainage; and
2. by limiting the development of **perched groundwater** conditions (Uchida et al. 2001).

If soil pipes become mechanically damaged and blocked, the increase in pore water pressure could trigger landslides (Ziemer 1992; Uchida et al. 2001), although this is highly dependent on local hillslope conditions (Keppeler and Brown 1998). Even under natural conditions, landslides may be triggered during large rainfall events when the capacity of the soil pipes is exceeded and pore water pressure increases rapidly (Uchida et al. 2001). In Japan, pipe outlets were evident in several of the scars left by landslides that occurred during heavy rainfall events. These landslides occurred on various bedrock types and on slopes that ranged from 20 to 84% (average 51%) (Uchida et al. 2001).

Soil pipes are particularly vulnerable to disturbance because they lie hidden beneath the soil surface. Although there is often minimal surface expression of their existence, wetter surrounding ground conditions and surface "blowholes" sometimes divulge their location. Increases in **bulk density** and moisture content, and decreases in hydraulic conductivity and infiltration, commonly follow forest harvesting. The collapse and closure of macropores and soil pipes from harvest-induced soil compaction is implicated as the probable cause of higher bulk density values (Herbauts et al. 1996; Miller et al. 1996; Williamson and Neilsen 2000). Therefore, before harvesting, it is important to identify the most hydrologically active zones and their spatial extent and connectivity within a basin.

After harvesting, and the subsequent increases in water inputs discussed above, pipeflow will likely play a more important role in hillslope hydrology. Actions that prevent soil pipes from collapsing (e.g., using slash to dissipate machine load or minimizing the number of machine passes) would help preserve their function and connectivity, and maintain hillslope drainage patterns. New soil pipes presumably form after existing ones are damaged, although it remains unclear how long this process takes and to what extent the pipe network is restored. Studies of soil pipe dynamics should be included in the hydrological monitoring of future operational trials.

3.4.4 Soil water chemistry The upland scrub forests of the north coast are thought to form a transition between productive upland forests and wetland forests. In Quebec, Dubé et al. (1995) showed that forest types transitional between upland forest and peatland are those most susceptible to water table rises after harvesting. As indicated earlier, however, on the north coast, the water table rise following harvesting in upland scrub forests is not expected to be as dramatic as in the swamp forests.

High water tables and the high levels of acidity in peatland systems are significant limitations to the nutrient cycling and forest productivity of these ecosystems. Nutrient availability is also limited by phenolic acids, which inhibit mineralization of nitrogen and phosphorus (de Montigny and Weetman 1990), and by high concentrations of lignins in cedar foliar litter (Prescott et al. 1995).

A high water table limits nutrient availability, and thus site fertility (Paavilainen and Päivänen 1995), largely by restricting rooting depth and often by maintaining anaerobic soil conditions. A high water table, therefore, controls **redox** conditions and the cycling of some important nutrient ions. Under aerobic conditions, decomposing soil organic matter releases nitrogen (N), sulphur (S), and phosphorus (P), which are oxidized to the ions NO_3, SO_4, and PO_4, respectively (Devito and Dillon 1993). During periods of high water table, anaerobic conditions predominate, which prevents the oxidization of nutrients to available forms. Our study shows that the highest ion concentrations in soil water occur in well-drained (productive forest) vegetation types which have deeper water tables and thicker aerobic zones.

We collected DOC data only in a pre-harvest setting, and have relatively little post-harvest data available from similar settings; therefore, our conclusions are preliminary. After harvesting, DOC levels could increase along with the greater water inputs to a site (Maloney et al. 2002). In addition, DOC concentrations are likely to rise as logging slash and debris decomposes, and as microbial activity increases in the warmer soil (Moore and Jackson 1989). Dissolved organic carbon concentrations in stream waters may remain elevated for up to 8–10 years after harvest, although the results from other studies in similar settings are varied (Moore 1989; Moore and Jackson 1989). If DOC increases a large amount after harvesting, water quality can be affected in several ways, including:

- increased water acidity,
- darker water with lower light penetration, and
- increased ability of the water to transport metals (Davies-Colley and Vant 1987; Driscoll et al. 1989; Driscoll et al. 1995).

These changes may potentially lower drinking water quality and have an undesirable effect on aquatic vegetation and fish populations. Dissolved organic carbon dynamics in pre- and post-harvest conditions requires further monitoring. If harvesting is to occur in sensitive watersheds where increases in DOC could have important downstream impacts, options to minimize these effects (e.g., reducing the rate of harvesting) should be examined during the planning stages.

A recent study of peatland and non-peatland watersheds in southeast Alaska showed that peatland-dominated watersheds had much higher average DOC concentrations in the streams than the non-peatland watersheds (D. D'Amore, U.S. Department of Agriculture, Juneau, Alaska, pers. comm., Dec. 2004). The researchers involved hypothesized that the peatland streams were better adapted to handle an increase of DOC after harvest than the non-peatland systems, and that the non-peatland systems were more susceptible to changes in stream biology resulting from increased DOC inputs after harvest.

Future operational trials in lower-productivity western redcedar–hemlock forests should include a soil water monitoring program. Such a program could better quantify changes in water table levels and ion concentrations in soil and stream waters associated with harvesting.

4.1 Introduction

Ecological plot data and field observations suggest that forest productivity on the outer coast reflects the interactions of many site variables, such as soil depth, the nature of surficial organic layers, the underlying mineral soil, bedrock geology, soil hydrology, slope, and disturbance history. The ecosystem processes component of the HyP^3 Project strives to understand how and why each of these factors affect site productivity and how they all interact to yield a specific forest ecosystem. This information is essential to identify those sites with potential for timber management, and to develop treatments that will maintain or improve site productivity.

Organic matter dynamics, including rates of forest humus and peat accumulation, is an important ecosystem process on the outer coast where organic soil layers play a vital role in determining successional trends and site productivity. The many peatlands that characterize the coastal landscape preserve a record of past conditions in their pollen and macrofossil profiles. These profiles provide the data against which we can compare current conditions, and predict future hydrological and related ecosystem responses to natural and human-influenced disturbances. Core sampling at several sites was conducted to reconstruct historical vegetation pattern and rates of peat accumulation. Production and decomposition rates within present-day vascular plant and moss communities were measured to estimate current rates of accumulation. These studies included detailed measurements of annual sphagnum moss productivity and colonization on both disturbed and undisturbed sites.

HyP^3 research also included studies on bedrock, soil properties, and site productivity relationships in both old-growth and second-growth stands across the spectrum of site series, from bog woodland and scrub forest, to productive upland forest. Studies assessing whether site manipulations to improve productivity are operationally feasible on lower-productivity wetter sites are also under way and are reported on in Chapter 6.

Finally, a model of ecosystem development and productivity is presented. We use this model to summarize the roles that bedrock geology, soil drainage, and disturbance history play in ecosystem development in the CWHvh2. This model represents a synthesis of the many individual findings of this project.

4.2 Succession and Disturbance

Our research on the role of succession and disturbance in vegetation dynamics will help to determine whether the lower-productivity western redcedar-dominated forests of the north coast can be harvested and regenerated sustainably. Understanding ecological processes, such as succession and disturbance, is critical to this determination because of the close ecological relationship between forests and bogs on the north coast, and the importance of disturbance in controlling bog and forest succession.

Ecological succession is defined as the change in species composition and cover of plant communities over time, ultimately leading to a climax or relatively stable vegetation type. This process is often accompanied by changes in soil composition and hydrology, which may be initiated by the vegetation itself, especially in wetlands. Bog development is an extreme case where the buildup of organic matter over hundreds or thousands of years (i.e., paludification) can produce conditions detrimental to tree growth. The gentle terrain of the Hecate Lowlands on the outer north coast, with its combination of high levels of precipitation and low levels of disturbance, favours paludification and bog development. This process is slowed on steeper terrain, where adequate soil drainage, slope instability, and occasional windthrow events tend to retard organic matter buildup and maintain forest productivity. Research suggests that sustainable forestry is only possible on sites where the natural inhibition of tree growth has not progressed too far and will not be promoted by harvesting practices. This section summarizes the relationship between natural disturbance and successional trends on the north coast.

4.2.1 Successional trends Evidence suggests that the plant communities of the outer north coast have long-term successional linkages. Successional histories spanning thousands of years are reconstructed by analyzing the peat stratigraphy of bogs using pollen, spores, and plant remains in peat cores, and radiocarbon (C^{14}) dating. Cores collected by Banner et al. (1983) near Prince Rupert show an 8000-year sequence, from an initial shore pine–red alder pioneer forest, to a Sitka spruce–western hemlock productive alluvial forest, then to a western redcedar–yellow-cedar scrub forest, and finally to a shore pine–yellow-cedar–western hemlock bog woodland. Some areas have shown further changes from the bog woodland to the open bog stage (Turunen and Turunen 2003). This shift in productivity and biomass allocation from trees to bryophytes appears to represent the dominant successional direction on the gentle slopes of the outer north coast. Some areas, however, show productive forests growing over peat deposits, which indicates that succession from wetland to forest also occurs on certain sites (Banner et al. 1983). Based on C^{14} dating, one such transition from wetland peat to upland forest humus in the Rainbow Lake area near Prince Rupert began approximately 2100 BP (before present) (Banner et al. 1983).

These successional trends highlight an important difference between the north coast and other less maritime areas of British Columbia. In most interior ecosystems of the province, successional pathways following disturbance (mainly fire) lead to a climax of productive forest. On the outer north coast, however, research suggests that the main long-term successional pathway, especially on the subdued landscape of the Hecate Lowlands, is from upland productive forest to lower-productivity forest types, and eventually to open bog (Klinger 1996). This successional pattern is not unique to the northwestern coast of North America. Other hypermaritime areas where sloping blanket bogs are extensive include Newfoundland, Great Britain, Ireland, Scandinavia, southern Chile, and southwestern New Zealand (Moore and Bellamy 1974). In the United Kingdom, forest-clearing activities may have played an important role in the development of open blanket bogs over large areas that were formerly forested (Moore 1987).

4.2.2 The role of climate in succession Based on studies of peat stratigraphy, evidence suggests that a period of peatland expansion, triggered by a cooler and wetter climatic trend, occurred during the middle part of the Holocene. Estimates of when this expansion began range from 3500 to 6000 BP (Heusser 1960; Mathewes and Heusser 1981; Banner et al. 1983; Hebda 1995) (Figure 4.1). On the north coast, this cooler and wetter trend was evidently sufficient to trigger succession from productive forest to scrub forest, thus setting the stage for the development of the blanket bog communities that characterize much of the area today.

4.2.3 The role of disturbance in succession Natural disturbance events on the north coast, as described in Chapter 2, play an important role in slowing and reducing organic matter accumulation on specific types of sites. The main types of natural disturbance on the north coast are landslides, windthrow, and fluvial activity.

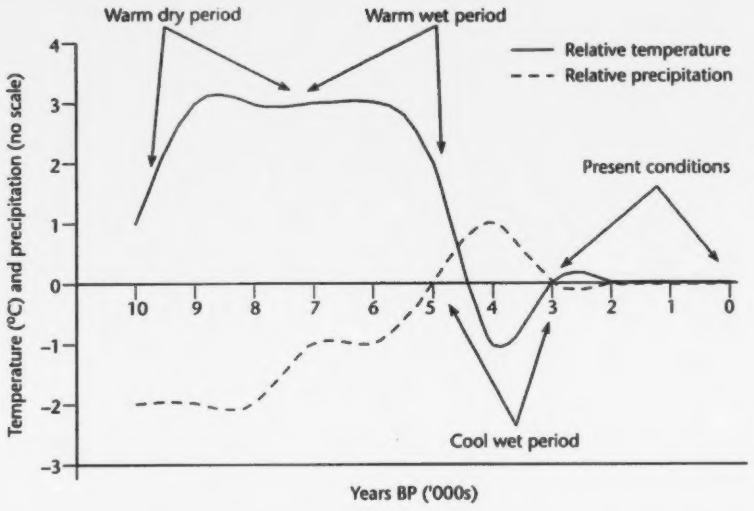

FIGURE 4.1 *Historical climatic conditions on the north coast relative to present conditions (interpreted from Hebda, 1995).*

These disturbance agents may cause large-scale, catastrophic (stand-replacing) disturbances or more localized gap disturbances. The churning of soil that occurs when a root wad is turned up or a landslide occurs speeds the decomposition of accumulated organic materials, brings mineral soil to the surface, and prevents or reverses **hardpan** formation (Bormann et al. 1995; Kayahara and Klinka 1997). After a windthrow disturbance, new organic horizons on the exposed tree root mounds can form at rates almost on par with those of long-term peat accumulation in peatlands (Bormann et al. 1995; Turunen and Turunen 2003). Without regular disturbance, this organic matter could continue to accumulate to considerable depths. Studies in southeast Alaska suggest that a disturbance return period of less than 200–350 years is needed to prevent tree roots from being confined to an increasingly thick organic horizon (Bormann et al. 1995). Longer disturbance return intervals may result in paludification and declining forest productivity. This relationship between disturbance and ecosystem productivity has also been studied in other parts of the world. There is growing scientific evidence from tropical, temperate, and boreal zones that an ecosystem "decline phase" is associated with the long-term absence of catastrophic disturbance (Wardle et al. 2004.)

Although most researchers agree that windthrow is an important disturbance agent on the coast, only limited documentation (especially for the north coast) exists concerning the extent of occurrence, return intervals, and the degree to which windthrow contributes to soil mixing across the landscape. A recent study in southeast Alaska (Hennon and McClellan 2003) found that many forests have no evidence of catastrophic windthrow, and that most tree death leading to canopy gap formation does not involve windthrow, or the uprooting necessary to cause soil mixing. For example, in areas of high wind exposure, more than 80% of the canopy-level gap makers were either dead-standing trees or had snapped off, neither of which contribute to soil mixing. In contrast, Bormann et al. (1995) found good evidence at several sites in southeast Alaska that windthrow played an important role in soil mixing and the reversal of paludification processes. Clearly, these studies require duplication and expansion on the north coast of British Columbia to better quantify the extent and effects of windthrow as both a small scale and catastrophic disturbance agent.

4.2.4 Management implications

Successional dynamics on the outer north coast has implications for forest management, both in the currently operable, productive forests and the lower-productivity western redcedar-dominated scrub forests, where little harvesting has occurred to date.

On the productive, currently operable sites, activities such as suspension cable logging and helicopter logging, which minimize surface disturbance and promote the development of young windthrow-resistant stands, may result in declining forest productivity over time. In this case, forest harvesting could act to lengthen the disturbance-return interval, and thereby reduce mineral soil disturbance, allowing organic matter to accumulate without the setbacks caused by windthrow-induced mixing of mineral and organic horizons (Bormann et al. 1995). This lack of disturbance could set the forest on a trajectory of organic matter accumulation that would be difficult to alter, especially where forests are managed on shorter rotations (≤ 100 years) which pre-empt the natural windthrow disturbance cycle.

On steep slopes susceptible to mass wasting (e.g., landslides, and debris flows), however, forest harvesting and road building may promote excessive disturbance with potentially negative effects on productivity, especially in the short term (see Figure 1.4). Studies on Haida Gwaii/the Queen Charlotte Islands show that timber harvesting can leave hillslopes susceptible to accelerated rates of mass wasting for 15–20 years following harvesting, or until stabilizing root systems re-establish. A comparison of mass wasting rates on the steep west coast of the Queen Charlotte Islands revealed a 15 times greater rate of occurrence on human-modified terrain than on forested terrain (Banner et al. 1989). The effects were greatest in areas of large clearcuts and road networks. In the natural forest landscape, mass wasting events are spread out in time and space, and are partially responsible for maintaining forest productivity. Where landslide activity is accelerated by human activities, however, negative effects often result, such as regeneration delays, initial loss of productivity near the slide source where soil is scoured to bedrock, and sediment loading and scouring of aquatic habitat. These very visible and immediate impacts tend to outweigh any potential improvement to long-term productivity that may occur in downslope areas. One of the major challenges we face is managing human-induced disturbances on a site-specific basis and in a way that attempts to mimic the natural system. Another challenge is gaining public acceptance that disturbances, whether natural or human-induced, can have positive as well as negative impacts on ecosystems.

In the lower-productivity forests that have escaped major disturbance events for thousands of years, harvesting and site preparation activities may provide the necessary surface disturbance and soil churning to mix mineral and organic horizons, improve nutrient availability and soil aeration, and retard organic matter accumulation. Given the appropriate site conditions (i.e., surface organic horizons underlain by mineral soil), such activities may improve tree productivity. This mixing may not be possible or beneficial, however, on sites with deep organic soils, or where mineral soils are very shallow or absent. Differences in soil properties and site productivity often reflect differences in bedrock geology. Mineral soils are often thinner over hard, massive granitic rocks than over softer metamorphic rocks, especially the schists (see section 4.5.1 for more detail). If timber harvesting expands into these lower-productivity forests, candidate sites must be carefully assessed using specific site and stand criteria so that any treatments applied will ensure acceptable second-growth regeneration and productivity. See Chapter 6 for details about the treatments applied in operational trials near Prince Rupert.

4.3 Paludification and Vegetation Dynamics

One of the most significant concerns regarding forest harvesting activities on lower-productivity, western redcedar-dominated sites is site degradation and reduced forest productivity. This concern is particularly relevant in north coastal British Columbia because paludification appears to have extended wetlands into formerly productive forests (Banner et al. 1983). Paludification is influenced by several factors including soil physical and chemical properties, long-term plant succession, and climatic changes. In several parts of the world, human activities, such as forest clearing and agriculture, also play a role in promoting paludification (Moore 1987; Warner et al. 1989). Forest clearing removes the rain-intercepting canopy and decreases evapotranspiration. This may cause a rise in the water table, facilitate the invasion by peat-forming sphagnum mosses, and potentially retard decomposition in saturated organic horizons.

Mosses are a major component of the vegetation in the hypermaritime, and peat accumulations are composed primarily of the remains of mosses mixed with sedges and other vascular plants. The response of mosses to forest management practices is of interest because of possible interactions with forest productivity and long-term vegetation successional pathways. Peat accumulates when moss production exceeds decomposition rates. To determine the peat accumulation potential of an area, measurements of productivity and decomposition rates are necessary. Acquiring this baseline information for natural peatlands will be useful for comparisons with managed areas.

Site preparation following harvesting may further promote the invasion of sphagnum mosses. Throughout British Columbia and in many other areas, mounding is used in wet forests to produce plantable sites, and to increase tree survival and growth (Londo 2001; Shaw and Banner 2001a). This treatment, however, can result in adjacent wet depressions, which may facilitate the invasion of sphagnum mosses and the paludification of previously forested ecosystems; therefore, it is imperative to understand the ecological relationship between moss growth and forest dynamics, and how this relationship is affected by forest management practices.

To create a more complete picture of how plant species, climate, microtopography, and ultimately site productivity interact on the scrub forest sites of the north coast, this section summarizes information from Asada (2002), Asada et al. (2003a, 2003b), Asada et al. (2004), and Asada and Warner (2005). It describes a series of experiments carried out at the Diana Lake and Port Simpson study sites (Figure 2.9) that deal with moss ecology, paludification, and vegetation and environment relationships. These experiments set out to:

- provide quantitative estimates of the growth and production of mosses and peatland community types on the outer coast of British Columbia;
- compare decomposition rates in different community types;
- document vegetation and environment relationships in natural and post-harvest communities;
- examine the possible effects of forest management practices on moss growth and productivity; and
- examine the effect of harvesting and mounding activities on vegetation, especially sphagnum mosses, at the Port Simpson operational trial.

4.3.1 Study approach Each of the study areas required a baseline classification of vegetation communities to provide a framework for further vegetation and environment studies. The cover of all plant species was recorded in quadrats along transects within the Diana Lake and Port Simpson study sites. These quadrats were grouped by classification analysis (Two-Way INdicator SPecies ANalysis – TWINSPAN; Hill 1979) into plant communities for each study area. Multivariate ordination analyses (detrended correspondence analysis [DCA] and canonical correspondence analysis [CCA]; Hill and Gauch 1980; ter Braak 1986) revealed the relationship between the resulting plant communities and the environment.[7] Environmental variables included water table and water chemistry measures, physical soil property measures, and slope. The Port Simpson study was conducted 8 years after harvesting and site preparation treatments. As no comparable pre-harvest data existed for the plant communities there, those of Diana Lake were examined to determine the likely changes at the harvested Port Simpson site.

Moss productivity was determined using nine abundant moss species at the Diana Lake site: *Sphagnum austinii* (Austin's peat-moss), *S. fuscum* (common brown peat-moss), *S. rubellum*, *S. papillosum* (fat peat-moss), *S. lindbergii* (brown-stemmed peat-moss), *S. tenellum* (soft peat-moss), *S. pacificum*, *Racomitrium lanuginosum* (hoary rock-moss), and *Pleurozium schreberi* (red-stemmed feathermoss). The selected mosses are the most representative peatland species in the region and have fairly specific habitat preferences (Table 4.1). Their growth was measured periodically and compared with local climatic parameters.

Growth measurements for all species were made at approximately 2-week intervals from May through August in 1999, and again on November 19, 1999. Measurements for *R. lanuginosum* and *P. schreberi* were also taken on July 11, 2000, and again on June 5, 2001. Winter growth

TABLE 4.1 *Growth and production of sphagnum and other mosses and their correlation with climatic parameters (adapted from Asada et al. 2003a)*

Species	Habitat preference	Growth^a (mm)	Production^a (g/m^2)	Correlation with mean daily precipitation^b	Correlation with mean daily temperature	Correlation with Climatic Index^b
Sphagnum austinii	Large hummock	10 ± 3c	280 ± 80a	0.15	0.03	0.35
S. fuscum	Large hummock	16 ± 4b	310 ± 70a	0.60	–0.24	0.72^{*}
S. rubellum	Small hummock	15 ± 3b	220 ± 50ab	0.85^{**}	–0.60	0.81^{*}
S. papillosum	Wet hummock	21 ± 4b	150 ± 50ab	0.75^{*}	–0.38	0.76^{*}
S. tenellum	Around pools and wet lawns	15 ± 4b	110 ± 40ab	0.84^{**}	–0.39	0.88^{**}
S. pacificum	Wet lawns	52 ± 9a	230 ± 50ab	0.74^{*}	–0.30	0.88^{**}
S. lindbergii	Depressions and small streams	43 ± 11a	260 ± 80a	0.73^{*}	–0.27	0.82^{*}
Racomitrium lanuginosum	Dry mounds in bog	9 ± 1–10 ± 1	360 ± 40–410 ± 50	0.59	0.18	0.95^{**}
Pleurozium schreberi	Bog woodland	20 ± 2–23 ± 3	290 ± 60–320 ± 80	0.47	0.25	0.89^{**}

a Growth and production for sphagnum mosses was estimated from May 21 to November 18, 1999; for other mosses the first-year growth (i.e., 1st number) is from July 16, 1999 to July 11, 2000, and the second-year growth (i.e., 2nd number) is from July 11, 2000 to June 5, 2001. Values are means ± standard error. Means followed by a different letter are significantly different (Tukey's HSD, $p < 0.05$, tested among sphagnum mosses only).

b Correlation between moss growth and climatic parameters is shown using Pearson correlation coefficients ($^{*}p < 0.05$; $^{**}p < 0.01$).

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[7] Refer to Asada et al. (2003b) for further details on classification and ordination approaches used in this study.

measurements for sphagnum species were impossible because of interference from snow; therefore, winter growth was estimated by using the relationship between the growth and the climate derived from the climatic index (described below). Estimated winter growth was added to summer growth to obtain estimates of annual growth; however, winter growth estimates do not take into account solar radiation differences between summer and winter. Other concerns about estimates of winter sphagnum growth are outlined in Asada et al. 2003a.

The climatic index produces a regression equation for each sphagnum species, and the winter growth was then estimated by inserting winter climate data into the equation. Note that the estimated values for **hummock**-forming sphagnum species should be treated with caution because the correlation coefficients between the growth and the climatic index, though high, were not significant. Annual production of each moss per unit area was estimated by multiplying the average annual linear growth by the average mass per unit length (Table 4.1).

To quantify concerns about paludification, the growth rates of three sphagnum species (*S. pacificum*, *S. rubiginosum*, and *S. rubellum*) were measured at Port Simpson and compared with those in unharvested areas at Diana Lake. Snow compression led to problems in measuring sphagnum growth; the maximum growth values were considered more accurate than mean values, and were therefore used for comparison purposes. In addition, the annual changes in area and volume covered by mosses, especially sphagnum, were measured at three Port Simpson locations.

Daily precipitation, and daily mean, maximum, and minimum temperatures were obtained from the meteorological station in the open bog of the Diana Lake site. These climate variables were treated as single parameters and also combined for the climate index. The climate index was developed to reflect the following assumptions, which were expected from previous studies:

- Growth of mosses is controlled primarily by precipitation.
- Precipitation cannot contribute to the moss growth if temperatures are lower than a certain threshold.
- The higher the temperature (up to moderate temperatures), the more precipitation relates to growth.

The climatic index adjusts the precipitation for each day by the temperature for that day. When the temperature is lower than a set threshold, the amount of precipitation is adjusted to zero, while precipitation on warmer days receives an increased weighting, based on the number of degrees above the threshold.

Moss growth and all climate parameters were expressed as means per day in a given period. Correlation coefficients between the growth and each climate parameter (i.e., precipitation, temperature, and climatic index) were calculated for each species. See Asada et al. (2003a) for a more detailed description and mathematical formula for the climatic index.

Measurements of current year's growth for the major herb, shrub, and lichen species, and the moss productivity data described above, were used to determine ecosystem productivity in the five community types found in the open peatland at Diana Lake (Asada 2002). Belowground productivity was estimated using root to shoot ratios found in other studies. The productivity of the entire peatland was estimated by applying a weighting to the production by the percent cover of each community type within the peatland. To estimate long- and short-term peat accumulation rates, radiocarbon and ^{210}Pb dating techniques were applied to surface cores collected from the Diana Lake study site (Turunen and Turunen 2003; Asada and Warner 2005).

The decomposition rate of organic material (*Sphagnum fuscum* was used as a standard material) was measured in nine plant communities at Diana Lake (e.g., bog woodland, bog forest, scrub forest, upland forest, and open peatland, which was further subdivided into five community types) and the four plant communities that were identified at Port Simpson. Organic matter placed in mesh bags was buried at a 10 cm depth in all plant communities, and also at a 25 and 45 cm depth in the bog woodland and open peatland at Diana Lake. Bags were removed after 1 and 2 years of incubation, and analyzed for mass loss and changes in carbon and nitrogen content.

4.3.2 Results: plant communities The TWINSPAN classification of quadrats at the Diana Lake research site identified nine plant communities. These communities were analogous to some of the site series identified by Banner et al. (1993) (see section 5.2), except that the open bog community was further subdivided into five sub-communities (Table 4.2). Site series at Diana Lake include: Western hemlock – Sitka spruce – Lanky moss (CWHvh2/04–productive forest), Western redcedar – Western hemlock – Salal (CWHvh2/01–scrub forest), Yellow-cedar – Western redcedar – Goldthread (CWHvh2/11–bog forest), Shore pine – Yellow-cedar – Sphagnum (CWHvh2/12–bog woodland), and Non-forested slope – blanket bog (CWHvh2/32); sub-communities identified within the open bogs were *Menyanthes trifoliata* pool, *Carex utriculata – Sphagnum lindbergii* depression, *Rhynchospora alba – S. tenellum* **lawn**, *Racomitrium lanuginosum* hummock, and *S. austinii* hummock.

An ordination of sample plots from the above plant communities is presented in Figure 4.2. Sample plots of similar species composition and cover are clustered on this graph. The distribution of plant communities on axis 1 correlated best with the minimum level of groundwater table fluctuation and slope. For example, open bog communities were found in areas of little slope and high water table, and forested communities were found in areas of greater slope and (at least seasonally) lower water tables. Although these two parameters are interrelated, steepness of slope influenced site drainage and soil water flux, and the water table influenced aerobic soil conditions and water chemistry. The distribution of productive forest (CWHvh2/04) on axis 2 correlated with the maximum level of groundwater table fluctuation and higher soil water conductivity parameters. This plant community grows in areas with consistently good drainage and is more influenced by groundwater in contact with mineral soils.

At the Port Simpson operational trial site, four plant communities were identified: two were related to wet hollows (*Sphagnum angustifolium* and *S. pacificum*); one was related to relatively dry (mesic) mounds (*Cornus canadensis – Hylocomium splendens*); and one was intermediate in moisture (*Polytrichum formosum – Sphagnum girgensohnii*) (Table 4.3). The unmounded area contained only one plant community that is generally related to mesic areas—*Cornus canadensis – Hylocomium splendens*. The mounded area contained a mixture of all four communities, reflecting the altered microtopography created by the mounding treatment.

The plant communities associated with the mesic mound and the intermediate moisture areas at Port Simpson were similar to those of the natural forest site at Diana Lake, while the two sphagnum-dominated communities were very different from those at Diana Lake. This suggests that the species in these communities are responding to habitat changes induced by forest management; the two sphagnum species that dominate the wet hollows are not commonly found in forested areas and therefore likely colonized the site after harvesting. These sphagnum-dominated communities were located mainly in fens in the larger Diana Lake area. A paleoecological study

TABLE 4.2 *Vegetation classified at the Diana Lake study site by Two-Way INdicator SPecies ANalysis (TWINSPAN) (adapted from Asada et al., 2003b)*

Community[a]		C1	C2	C3	C4	C5	C6	C7	C8	C9
Number of plots		3	5	5	11	5	9	14	9	5
Species name	**Stratum**[b]									
Trees										
Abies amabilis (Dougl. ex Loud.) Dougl. *ex* Forbes	9	5.0[c]	–	–	–	–	–	–	–	–
	8	0.7	0.6	–	–	–	–	–	–	–
	7	1.7	–	–	–	–	–	–	–	–
	6	1.7	–	–	–	–	–	–	–	–
	5	1.3	–	–	–	–	–	–	–	–
	4	2.0	–	–	–	–	–	–	–	–
Tsuga heterophylla (Raf.) Sarg.	9	5.0	–	–	–	–	–	–	–	–
	8	3.3	3.6	–	–	–	–	–	–	–
	7	2.3	4.0	0.8	0.3	–	–	–	–	–
	6	3.7	3.8	2.4	0.3	–	–	–	–	–
	5	2.0	–	1.2	–	–	–	–	–	–
	4	1.7	0.4	–	–	–	–	–	–	–
Picea sitchensis (Bong.) Carr.	9	–	0.6	–	–	–	–	–	–	–
	8	–	0.8	–	–	–	–	–	–	–
	7	–	1.2	–	–	–	–	–	–	–
	6	–	1.2	–	–	–	–	–	–	–
	5	–	0.4	–	–	–	–	–	–	–
Tsuga mertensiana (Bong.) Carr.	8	–	2.6	–	–	–	–	–	–	–
	7	–	1.0	1.8	–	–	–	–	–	–
	6	–	–	1.2	–	–	–	–	–	–
	5	–	0.2	0.8	–	–	–	–	–	–
Thuja plicata Donn *ex* D. Don	9	2.3	1.6	–	–	–	–	–	–	–
	8	–	4.4	0.4	–	–	–	–	–	–
	7	–	2.6	2.2	–	–	–	–	–	–
	6	–	1.2	0.6	–	–	–	–	–	–
	5	–	0.2	1.6	–	–	–	–	–	–
	4	–	0.6	–	–	–	–	–	–	–
Chamaecyparis nootkatensis (D. Don) Spach	8	–	1.6	1.0	–	–	–	–	–	–
	7	–	1.4	2.8	–	–	–	–	–	–
	6	–	0.4	2.6	–	–	–	–	–	–
	5	–	–	3.2	2.2	–	0.4	–	–	–
	4	–	1.0	3.2	1.0	1.0	–	–	–	–
Pinus contorta Dougl. *ex* Loud. var. *contorta*	8	–	–	1.4	–	–	–	–	–	–
	7	–	–	3.0	0.9	–	–	–	–	–
	6	–	–	0.2	1.7	–	0.4	–	–	–
	5	–	–	1.4	–	–	0.7	–	–	–
	4	–	–	–	0.3	–	0.6	–	–	–
Shrubs										
Vaccinium parvifolium Sm.	6	3.3	0.2	–	–	–	–	–	–	–
	5	0.7	0.6	0.8	–	–	–	–	–	–
	4	1.7	1.0	0.8	–	–	–	–	–	–
Oplopanax horridus (Smith) Miq.	6	1.0	0.8	–	–	–	–	–	–	–
	5	0.3	0.2	–	–	–	–	–	–	–
	4	0.7	–	–	–	–	–	–	–	–
Vaccinium alaskaense Howell	6	2.0	4.0	–	–	–	–	–	–	–
	5	1.0	0.6	1.2	–	–	–	–	–	–
	4	0.3	1.8	1.0	–	–	–	–	–	–

TABLE 4.2 *Continued*

Community[a]		**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Number of plots		**3**	**5**	**5**	**11**	**5**	**9**	**14**	**9**	**5**
Species name	**Stratum**[b]									
Shrubs										
Menziesia ferruginea Sm.	6	–	4.0	1.2	–	–	–	–	–	–
	5	1.7	–	1.0	–	–	–	–	–	–
	4	–	0.6	0.4	–	–	–	–	–	–
Vaccinium ovalifolium Sm.	6	–	1.8	–	–	–	–	–	–	–
	5	–	1.0	1.4	–	–	–	–	–	–
	4	–	0.4	–	–	–	–	–	–	–
Gaultheria shallon Pursh	5	–	2.6	0.6	0.2	–	–	–	–	–
	4	–	2.0	3.4	0.3	–	–	–	–	–
Ledum groenlandicum Oeder	4	–	–	2.0	1.5	1.4	1.2	0.1	0.1	–
Myrica gale L.	5	–	–	–	0.3	–	–	–	–	–
	4	–	–	–	0.5	–	–	–	–	–
Vaccinium uliginosum L.	4	–	–	0.4	1.5	0.4	1.3	0.1	–	–
Juniperus communis L.	4	–	–	–	1.1	0.8	1.3	0.1	–	–
Kalmia microphylla (Hook.) Heller *occidentalis* (Small) Taylor & MacBryde	4	–	–	1.4	1.5	1.0	1.9	0.3	0.8	–
Herbs and Dwarf Shrubs										
Cornus canadensis L.	3	2.3	3.4	3.4	1.5	1.2	1.1	–	0.1	–
Tiarella trifoliata L.	2	1.7	–	–	–	–	–	–	–	–
Rubus pedatus J. E. Sm.	3	1.0	1.8	0.2	–	–	–	–	–	–
Listera cordata (L.) R. Br.	2	0.7	1.0	0.4	–	–	–	–	–	–
Streptopus lanceolatus (Ait.) Reveal var *curvipes* (Vail) Reveal.	2	0.3	0.8	0.4	–	–	–	–	–	–
Lysichiton americanus Hult. & St. John	2	–	2.2	–	–	–	–	–	–	–
Moneses uniflora (L.) A. Gray	2	–	0.4	–	–	–	–	–	–	–
Linnaea borealis L.	3	–	1.6	1.4	0.5	–	–	–	–	–
Coptis aspleniifolia Salisb.	2	–	1.6	1.8	0.1	–	–	–	–	–
Vaccinium vitis–idaea L. ssp. *minus* (Lodd.) Hult.	3	–	–	1.4	0.4	–	–	–	–	–
Vaccinium caespitosum Michx.	3	–	–	1.8	–	–	–	–	–	–
	4	–	–	1.4	0.3	0.2	–	–	–	–
Fauria crista–galli (Menzies *ex* Hook.) Makino	2	–	0.4	3.8	3.2	0.4	–	–	–	–
Rubus chamaemorus L.	3	–	–	0.2	0.6	0.8	–	–	–	–
Oxycoccus oxycoccus (L.) MacM.	3	–	–	0.2	1.0	0.6	0.6	0.1	0.4	–
Sanguisorba officinalis L.	2	–	–	1.2	2.1	0.4	2.0	0.6	1.4	0.2
Drosera rotundifolia L.	2	–	–	1.0	2.2	2.0	0.6	2.9	2.0	–
Empetrum nigrum L.	3	–	–	1.0	1.8	1.8	0.9	0.1	–	–
Trientalis europaea L. ssp. *arctica* (Fisch. ex Hult.) Hult.	2	–	–	0.4	0.8	0.2	0.7	0.1	0.2	
Andromeda polifolia L.	3	–	–	0.2	1.0	0.6	1.4	1.1	1.1	–
Trichophorum cespitosum (L.) Hartm.	2	–	–	0.2	1.7	1.2	2.0	0.1	1.0	–
Eriophorum angustifolium Honck.	2	–	–	0.2	1.4	0.2	1.7	1.1	1.0	3.0
Coptis trifolia (L.) Salisb.	2	–	–	0.2	1.1	0.4	0.8	–	0.2	–
Carex livida (Wahlenb.) Willd. var. *radicaulis* Paine	2	–	–	0.2	0.7	0.2	0.1	–	1.0	1.0
Rhynchospora alba (L.) Vahl	2	–	–	–	0.9	–	1.6	3.4	1.6	1.2
Triantha glutinosa (Michx.)Baker	2	–	–	–	0.7	0.4	–	0.1	0.2	–
Carex pauciflora Lightf.	2	–	–	–	0.5	–	0.1	–	0.6	–
Gentiana douglasiana Bong.	2	–	–	–	0.4	–	0.6	–	0.2	–
Dodecatheon jeffreyi van Houtte	2	–	–	–	0.3	–	–	–	0.8	–
Geum calthifolium Menzies *ex* J. M. Smith	2	–	–	–	0.2	–	–	0.1	0.6	–

TABLE 4.2 *Continued*

Community[a]		**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Number of plots		**3**	**5**	**5**	**11**	**5**	**9**	**14**	**9**	**5**
Species name	**Stratum**[b]									
Herbs and Dwarf Shrubs										
Agrostis aequivalvis (Trin.) Trin.	2	–	–	–	0.2	–	0.1	–	0.3	–
Drosera anglica Huds.	2	–	–	–	–	1.0	0.1	2.7	0.4	–
Carex pluriflora Hult.	2	–	–	–	–	–	0.2	0.2	0.9	0.8
Carex utriculata Boott	2	–	–	–	–	–	0.1	–	2.2	0.2
Scheuchzeria palustris L. ssp. *americana* (Fern.) Hult.	2	–	–	–	–	–	–	0.3	0.1	0.2
Menyanthes trifoliata L.	2	–	–	–	–	–	–	–	0.9	4.6
Ferns / Clubmosses										
Gymnocarpium dryopteris (L.) Newman	2	1.3	–	–	–	–	–	–	–	–
Polystichum munitum (Kaulf.) K.B. Presl	2	0.7	–	–	–	–	–	–	–	–
Blechnum spicant (L.) Roth	2	1.3	1.6	–	–	–	–	–	–	–
Lycopodium annotinum L.	2	–	0.4	1.2	0.4	–	–	–	–	–
Bryophytes										
Rhytidiadelphus loreus (Hedw.) Warnst.	1	4.7	2.4	3.0	0.2	–	–	–	–	–
Rhizomnium glabrescens (Kindb.) T. Kop	1	2.7	1.8	1.6	–	–	–	–	–	–
Hylocomium splendens (Hedw.) Schimp.	1	2.7	4.2	3.0	0.1	–	–	–	–	–
Eurhynchium oreganum (Sull.) Jaeg.	1	2.3	0.2	–	–	–	–	–	–	–
Sphagnum rubiginosum Flatb.	1	1.7	4.0	–	–	–	–	–	–	–
Scapania bolanderi Aust.	1	1.3	0.2	–	–	–	–	–	–	–
Plagiothecium undulatum (Hedw.) Schimp.	1	1.0	1.0	0.8	0.1	–	–	–	–	–
Plagiochila porelloides (Torr. ex Nees) Lindenb	1	0.7	1.0	0.2	–	–	–	–	–	–
Riccardia latifrons Lindb.	1	0.3	0.2	–	–	–	–	–	–	–
Hookeria lucens (Hedw.) Sm.	1	0.3	0.8	–	–	–	–	–	–	–
Sphagnum pacificum Flatb.	1	–	2.6	3.2	1.7	–	–	–	–	–
Pellia neesiana (Gott.) Limpr.	1	–	1.0	0.2	–	–	–	–	–	–
Sphagnum papillosum Lindb.	1	–	0.4	0.2	1.0	–	1.0	1.1	2.2	–
Sphagnum magellanicum Brid.	1	–	0.4	–	0.2	–	–	–	–	–
Calypogija sphagnicola (H. Arnell & J. Perss.) Warnst. & Loeske	1	–	0.4	–	0.1	–	–	–	–	–
Sphagnum capillifolium (Ehrh.) Hedw.	1	–	0.2	2.6	1.5	–	–	–	–	–
Pleurozium schreberi (Brid.) Mitt.	1	–	–	3.0	1.5	–	–	–	–	–
Sphagnum rubellum Wils.	1	–	–	1.8	2.5	1.6	1.4	0.9	0.7	–
Sphagnum fuscum (Schimp.) Klinggr.	1	–	–	1.6	3.2	1.0	1.6	0.4	–	–
Bazzania trilobata (L.) S. Gray	1	–	–	1.6	0.3	–	–	0.1	–	–
Sphagnum tenellum (Brid.) Bory	1	–	–	1.0	0.5	–	0.7	3.4	1.1	–
Hypnum callichroum Funck *ex* Brid.	1	–	–	1.0	–	–	–	–	–	–
Hepatophyta (Jungermanniales) spp.	1	–	–	0.8	–	–	–	–	–	–
Dicranum majus Sm. var. *majus*	1	–	–	0.8	–	–	–	–	–	–
Ptilium crista–castrensis (Hedw.) De Not.	1	–	–	0.4	0.5	–	–	0.1	–	–
Aulacomnium palustre (Hedw.) Schwaegr.	1	–	–	0.4	–	–	–	–	–	–
Sphagnum recurvum P. Beauv.	1	–	–	0.2	0.5	–	–	–	–	–
Mylia anomala (Hook.) S. Gray	1	–	–	0.2	0.8	0.2	0.1	0.2	–	–
Racomitrium lanuginosum (Hedw.) Brid.	1	–	–	–	0.3	–	3.0	0.4	0.6	–
Sphagnum austinii Sull.	1	–	–	–	–	5.0	0.7	–	–	–

TABLE 4.2 *Concluded*

Community[a]		**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Number of plots		**3**	**5**	**5**	**11**	**5**	**9**	**14**	**9**	**5**
Species name	**Stratum**[b]									
Bryophytes										
Sphagnum compactum DC.	1	–	–	–	–	–	0.1	0.4	0.7	–
Sphagnum lindbergii Schimp.	1	–	–	–	–	–	–	0.3	2.8	–
Scapania undulata (L.) Dum.	1	–	–	–	–	–	–	–	0.3	–
Lichens										
Cladina portentosa ssp. *pacifica* (Ahti) Ahti	1	–	–	1.0	2.5	2.0	3.2	1.7	0.8	–
Siphula ceratites (Wahlenb.) Fr.	1	–	–	–	–	–	–	2.4	–	–

[a] C1 = Western hemlock – Sitka spruce – Lanky moss (CWHvh2/04–productive forest); C2 = Western redcedar – Western hemlock – Salal (CWHvh2/01–scrub forest); C3 = Yellow-cedar – Western redcedar – Goldthread (CWHvh2/11–bog forest); C4 = Shore pine – Yellow-cedar – Sphagnum (CWHvh2/12–bog woodland). C5–C9 are sub-communities in the Sphagnum open peatland (CWHvh2/32): C5 = *Sphagnum austinii* hummock; C6 = *Racomitrium lanuginosum* hummock; C7 = *Rhynchospora alba – Sphagnum tenellum* lawn; C8 = *Carex utriculata – Sphagnum lindbergii* depression; and C9 = *Menyanthes trifoliata* pool.

[b] Numbers in the stratum column denote the stratum in which the species are categorized: 1 = bryophyte/lichen stratum; 2 = herb stratum; 3 = dwarf shrub stratum; 4 = low shrub stratum; 5 = shrub stratum; 6 = tall shrub stratum; 7 = tree stratum; 8 = tall tree stratum; and 9 = very tall tree stratum.

[c] Values are means of categories of abundance within each community type. Only species whose values are greater than 0.2 in any community are listed.

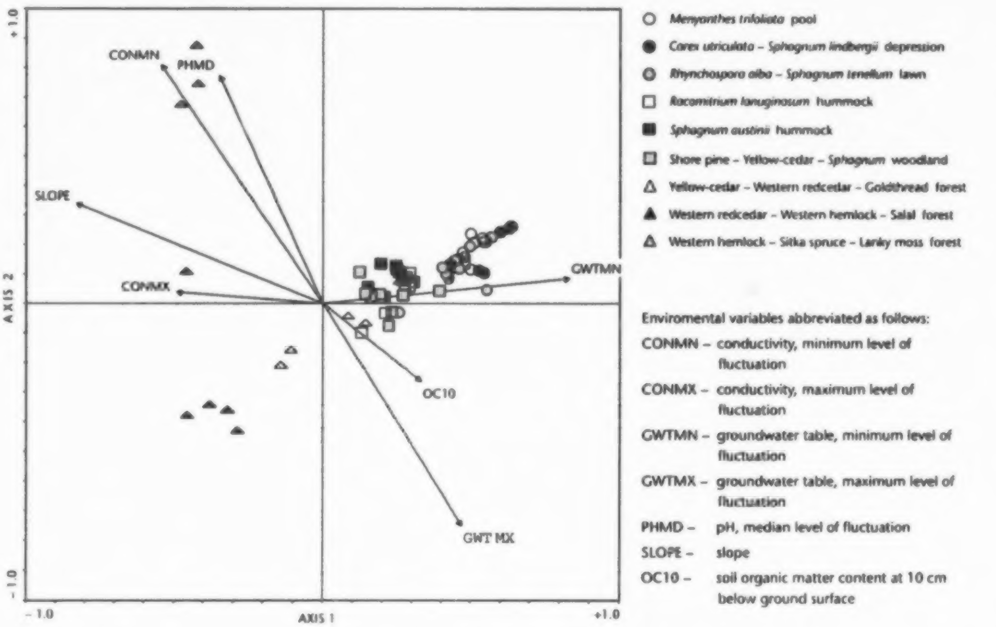


FIGURE 4.2 *Canonical correspondence analysis of Diana Lake study plots.* TWINSPAN *(Two-Way INdicator SPecies ANalysis) communities (described in Table 4.2) are superimposed (adapted from* Asada et al., 2003b*).*

TABLE 4.3 *Vegetation classified at the Port Simpson study site by Two-Way INdicator SPecies ANalysis (TWINSPAN) (adapted from Asada et al., 2004)*

	Community[a] (# of plots)			
Species	**P1 (18)**	**P2 (76)**	**P3 (156)**	**P4 (27)**
Shrubs and seedlings				
Vaccinium alaskaense Howell	0.3[b]	–	0.2	–
Menziesia ferruginea Sm.	0.2	1.2	1.4	–
Gaultheria shallon Pursh	0.1	0.6	1.8	0.4
Tsuga heterophylla (Raf.) Sarg.	–	0.4	0.2	–
Vaccinium ovalifolium Sm.	–	0.3	0.3	–
Thuja plicata Donn ex D. Don	–	–	0.2	0.1
Herbs				
Lysichiton americanus Hult. & St. John	0.4	0.1	0.1	0.4
Maianthemum dilatatum (A. Wood) Nels. & J. F. Macbr.	0.3	0.5	2.6	0.1
Cornus canadensis L.	0.1	0.7	2.9	0.1
Rubus pedatus J.E. Sm.	–	0.3	0.4	0.1
Linnaea borealis L.	–	0.1	2.0	–
Dryopteris expansa (K.B. Presl) Fraser-Jenkins & Jermy	–	0.1	0.2	–
Coptis aspleniifolia Salisb.	–	–	0.6	–
Blechnum spicant (L.) Roth	–	–	0.5	–
Schoenoplectus tabernaemontani (K. C. Gmel.) Palla	–	–	–	0.2
Bryophytes				
Sphagnum angustifolium (C. Jens. ex Russ.) C. Jens.	2.6	0.1	0.2	0.2
Polytrichum formosum Hedw.	1.5	2.8	0.5	0.4
Dicranum fuscescens Turn. var. *fuscescens*	1.4	0.3	0.1	–
Sphagnum palustre L.	0.8	0.2	0.0	–
Sphagnum tenerum Sull. & Lesq.	0.5	0.0	–	–
Sphagnum rubellum Wils.	0.4	0.3	0.3	0.1
Sphagnum girgensohnii Russ.	0.2	1.3	0.6	0.3
Polytrichum juniperinum Hedw.	0.2	0.1	0.2	–
Cephalozia bicuspidata (L.) Dum. ssp. *bicuspidata*	0.1	0.5	0.1	–
Dicranella heteromalla (Hedw.) Schimp.	0.1	1.1	0.6	–
Plagiothecium undulatum (Hedw.) Schimp.	0.1	0.3	0.5	–
Scapania bolanderi Aust.	0.1	0.8	1.1	–
Rhytidiadelphus loreus (Hedw.) Warnst.	0.1	0.7	1.8	–
Hylocomium splendens (Hedw.) Schimp.	0.1	0.4	2.5	–
Sphagnum pacificum Flatb.	–	0.6	0.3	4.9
Pogonatum dentatum (Brid.) Brid.	–	0.3	–	–
Lophozia cf. *wenzelii* (Nees) Steph. var. *wenzelii*	–	0.3	0.1	–
Sphagnum capillifolium (Ehrh.) Hedw.	–	0.1	0.6	–
Pleurozium schreberi (Brid.) Mitt.	–	–	0.2	–
Barbilophozia floerkei (Web. & Mohr) Loeske var. *floerkei*	–	–	0.2	–
Dicranum scoparium Hedw.	–	–	0.3	–
Calypogeja muelleriana (Schiffn.) K.Müll. ssp. *muelleriana*	–	–	0.3	–

[a] P1: *Sphagnum angustifolium* community; P2: *Polytrichum formosum – Sphagnum girgensohnii* community; P3: *Cornus canadensis – Hylocomium splendens* community; and P4: *Sphagnum pacificum* community.

[b] Values are means of categories of abundance within each community defined by pseudospecies cut levels of TWINSPAN. Values are rounded to 0.1, and only species whose values are greater than 0.1 in any community are listed.

(Turunen and Turunen 2003) showed that one of these areas had undergone paludification relatively recently, which helps to confirm the pioneering capacity of *S. pacificum* and *S. angustifolium* in natural systems, as well.

The multivariate ordination analysis of the relationship between environmental variables and plant communities showed that the distribution of these communities correlated best with water table depth; pH, conductivity, and slope showed up as secondary factors. This indicates that the plants respond mainly to soil moisture and related conditions. Pools formed by the mounding, possibly in combination with a post-harvest rise in water table, appear to provide habitat conditions that allow colonization by these species (Figure 4.3). The acidifying ability of sphagnum likely creates water chemistry gradients (i.e., pH and conductivity); these gradients, in turn, facilitate additional sphagnum growth and limit the potential for vascular plant establishment and growth (van Breeman 1995).

Sphagnum rubiginosum, and the taxonomically closely related species, *Sphagnum girgensohnii*, commonly inhabit forested areas and occur at both the Port Simpson and Diana Lake sites. At Port Simpson, however, these species were more abundant in the mounded portion of the harvested area than in the unmounded portion. The presence of pools in the mounded area is likely responsible for the persistence of these species, which are often associated with the pits formed by blowdowns in the forest (Noble et al. 1984). In addition, *S. pacificum* and *S. angustifolium*, which are closely related to known pioneering species such as *S. fallax* (Grosvernier et al. 1997; Buttler et al. 1998), likely colonized the hollows created by the mounding process after harvesting. Mounding as a site preparation treatment appears, therefore, to facilitate the persistence or colonization of several sphagnum species.

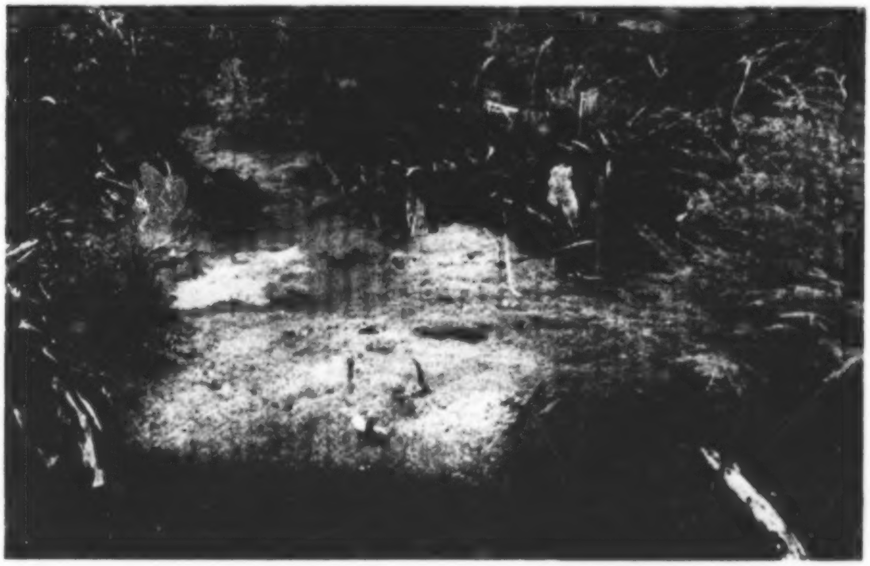


FIGURE 4.3 *Depressions created by mounding at Port Simpson filled in with sphagnum moss after 6 years.*

4.3.3 Moss growth and climate parameters Figures 4.4 and 4.5 illustrate the growth patterns of *Pleurozium schreberi* and four of the sphagnum species studied in relation to climatic parameters. For the sphagnums, the hollow and the wet lawn species (i.e., *S. lindbergii* and *S. pacificum*) grew more than the hummock-forming species (i.e., *S. austinii* and *S. fuscum*) (Figure 4.5); however, the growth rates of the hummock-forming species were less variable than the hollow and the wet lawn species. Hummock species grew even during the dry period, albeit slowly, but the hollow and lawn species did not.

Generally, the growth pattern of *Racomitrium lanuginosum*, *P. schreberi* (these two species showed very similar growth patterns), and the seven sphagnum species reflected the precipitation pattern rather than that of temperature (Figures 4.4 and 4.5). Correlation coefficients between precipitation and growth were higher than those between temperature and growth for all species (Table 4.1), and five species showed statistically significant correlations.

The climatic index showed a much higher correlation with growth than either precipitation or temperature alone for all species except *S. rubellum* (Figures 4.4 and 4.5; Table 4.1). Growth was significantly correlated with the climatic index for all of the species except *S. austinii*.

When the lowest temperature above which vegetative growth occurs is used as the exploratory temperature threshold in the index, the climatic index should have the highest correlation with moss growth. Correlation coefficients for the growth of *R. lanuginosum* and *P. schreberi* were highest with the climatic index when daily mean temperature was set at 5°C, which implies that this is the temperature threshold for the growth of these two species. For the sphagnum species, the highest correlation with the climatic index was at 0°C for most species, 5°C lower than that for *R. lanuginosum* and *P. schreberi*. These growth threshold temperatures are preliminary, however, because of difficulties in obtaining winter growth measurements. See Asada et al. (2003a) for more detail on the estimation methods for temperature thresholds.

At Diana Lake, *Sphagnum pacificum* was the fastest-growing species (i.e., vertical stem growth), with an estimated growth of 52 mm between May and November 1999 (Table 4.1); *S. lindbergii* also had rapid stem growth of 43 mm during the same period. *S. austinii* had the slowest growth rate, which was estimated at 10 mm. *S. fuscum*, *S. rubellum*, and *S. tenellum* showed similar growth rates of about 15 mm.

The most productive sphagnum species (total annual biomass) were the hummock-forming *S. fuscum* and *S. austinii* (Table 4.1). Although the vertical growth of the hummock species was small, their dense growth form contributed to this high productivity. In particular, the bulk density of *S. austinii* was the highest among the species studied. Lindholm and Vasander (1990) showed the same trend for *S. fuscum*. The next highest productivity values were observed in *S. lindbergii* and *S. pacificum*. The high vertical growth of both species contributed considerably to this productivity, as they had the lowest bulk density among the species studied. The productivity of *S. rubellum* was close to that of *S. pacificum*, but this depended more on bulk density than on vertical growth. The vertical growth and bulk density of *S. papillosum* were relatively low, resulting in low overall productivity. Although *S. tenellum* had the highest number of capitula, or compact heads of individual *Sphagnum* plants, this species had the lowest productivity per area among the species studied because of its low bulk density (Table 4.1). The annual stem growth of *P. schreberi* was about 22 mm/yr compared to about 9 mm/yr for *R. lanuginosum* (Table 4.1); however, the annual production of *R. lanuginosum* was higher than that of *P. schreberi* because of

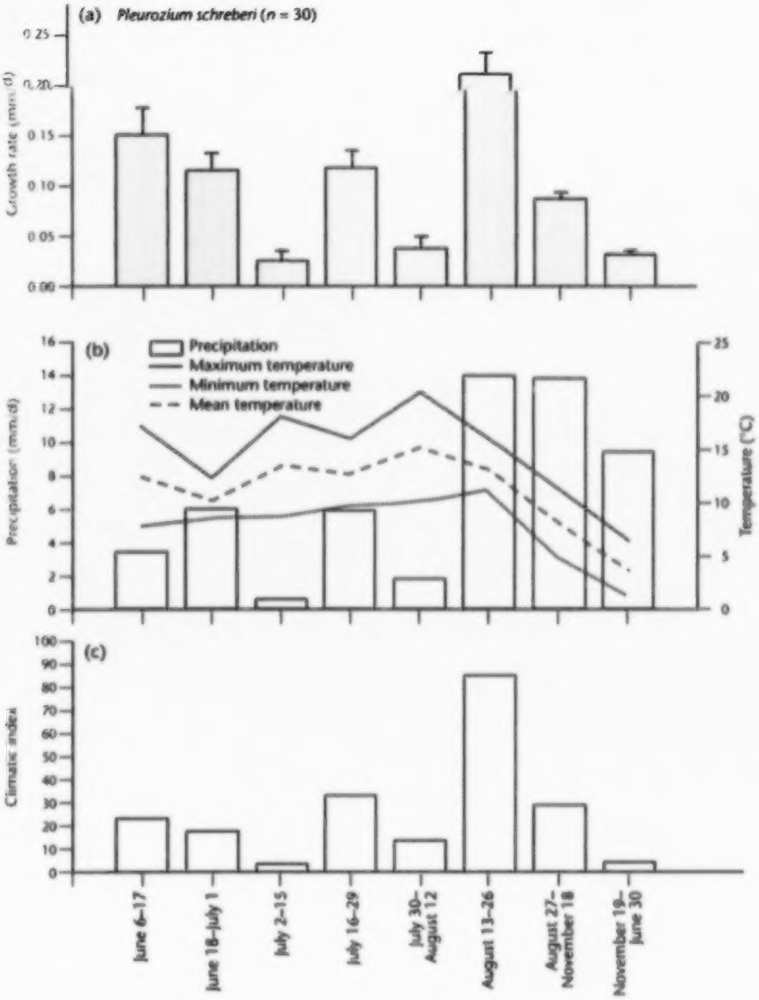


FIGURE 4.4 *Growth patterns of* Pleurozium schreberi *in relation to climatic parameters for eight consecutive sampling intervals from June 1999 to July 2000: (a) mean daily growth (±1 SE); (b) mean daily precipitation, and daily maximum, minimum, and mean temperatures; (c) mean daily climatic index (when temperature = daily mean, and temperature threshold, x = 7) (adapted from Asada et al., 2003a, see reference for the mathematical formula for climatic index).*

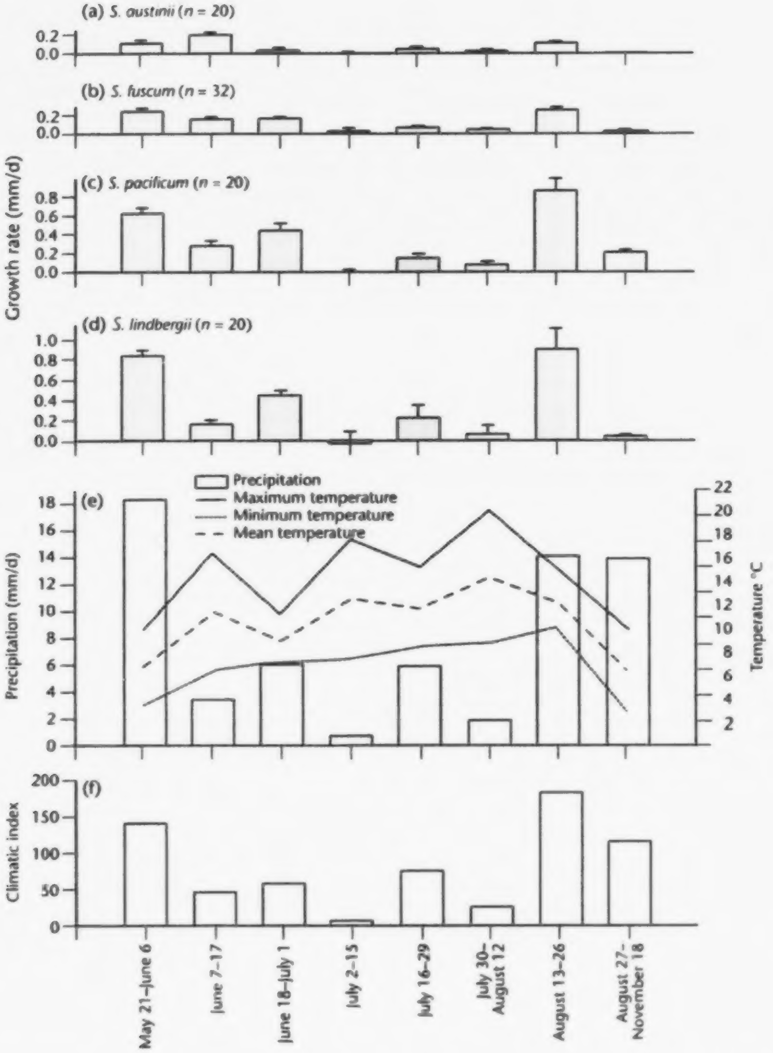


FIGURE 4.5 *Growth patterns of four Sphagnum species in relation to climatic parameters for eight consecutive sampling intervals, May–November 1999: (a)–(d): mean daily growth (±1 SE) of sphagnum; (e) mean daily precipitation, and daily maximum, minimum, and mean temperatures; (f) mean daily climatic index (when temperature = daily mean, and temperature threshold x = 0) (adapted from Asada et al., 2003a, see reference for the mathematical formula for climatic index).*

its denser growth form. Based on the comparison of measurements of the most widely measured species, *Sphagnum fuscum*, the productivity of sphagnum mosses tended towards the top of the range of similar measurements made in other sphagnum-dominated peatlands in Canada (Asada 2002).

When the maximum growth rates of three common sphagnum species at the Port Simpson and Diana Lake sites were compared, *S. rubiginosum* showed considerably higher growth rates in the cutover area (85 mm/yr vs. 55 mm/yr) than in the natural area, the other two species had similar growth rates at both areas. This indicates that the conditions in the mounded cutblock may enhance the growth rate of *S. rubiginosum*.

The area and volume covered by mosses, especially sphagnum, expanded considerably in 1 year, particularly at the two wetter locations (Figure 4.6), while at the driest location the changes were not nearly as great. This shows that moisture is important in moss colonization and that mosses are actively colonizing more area.

Total ecosystem productivity among the five open peatland communities was highest on the *Sphagnum austinii* hummocks and lowest in the *Rhynchospora alba – Sphagnum tenellum* lawns (Table 4.4). Moss growth provided the greatest amount of productivity to all communities except the *Menyanthes trifoliata* pool. The total **net primary productivity** (NPP) for the bog was not high because the bog was dominated by the low productivity *Rhynchospora alba – Sphagnum tenellum* lawns. Peatlands with a different plant community composition (e.g., one dominated by *Sphagnum austinii* hummocks) would likely have a much higher NPP.

The rate of mass loss was not statistically different among the communities at the Port Simpson site, ranging from 15.7 to 17.7% (Table 4.5). The mass loss rates at the Port Simpson site were not significantly different from any communities at the Diana Lake site. At the Diana site, decomposition was fastest in the *Sphagnum austinii* hummocks and *Carex utriculata – Sphagnum lindbergii* depressions and slowest in *Menyanthes trifoliata* pools in the open peatland (Asada et al. 2004). Most of the mass loss occurred in the first year, a result which is in agreement with other studies. When mass loss was examined in relation to the water table, decomposition was significantly

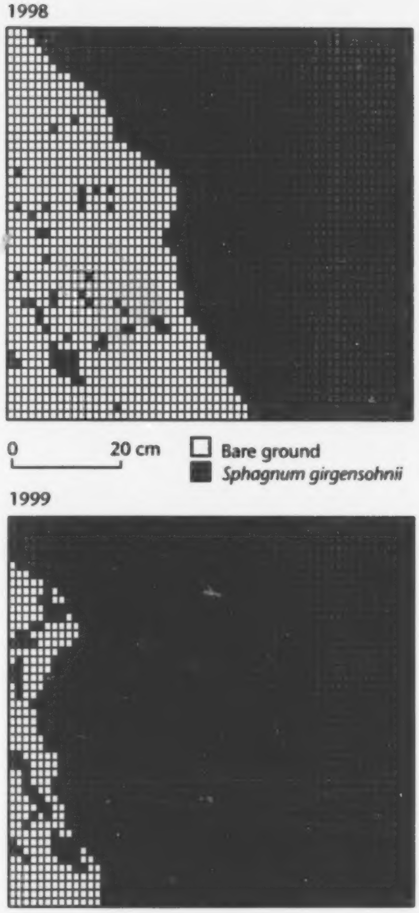


FIGURE 4.6 *Change in cover of* Sphagnum girgensohnii *between 1998 and 1999 at one of the three Port Simpson sites (adapted from Asada et al., 2004).*

TABLE 4.4 *Estimated total net primary production (NPP; g/m² per year)*[a] *for the five representative micro-communities in the open bog at the Diana Lake study site (adapted from Asada, 2002)*

	Above ground NPP	Below ground NPP[b]		Total NPP		Range of A/B ratio[c]
		Minimum	Maximum	Minimum	Maximum	
Menyanthes trifoliata pool	104.7 ± 23.5a	85.5 ± 18.6a	164.6 ± 40.0ab	190.2 ± 41.5ab	269.3 ± 62.8ab	1.2–0.6
Carex utriculata – Sphagnum lindbergii depression	300.9 ± 32.4b	121.5 ± 38.8a	194.6 ± 41.5ab	422.5 ± 63.8ac	495.6 ± 51.8c	2.5–1.5
Rhynchospora alba – Sphagnum tenellum lawn	163.6 ± 23.6a	15.1 ± 2.9b	71.6 ± 13.9a	178.7 ± 25.2b	235.2 ± 32.9b	10.8–2.3
Racomitrium lanuginosum hummock	291.3 ± 30.5b	43.9 ± 5.0a	164.7 ± 19.2b	335.2 ± 30.4ac	456.1 ± 35.4ac	6.6–1.8
Sphagnum austinii hummock	402.4 ± 14.5b	24.1 ± 9.1ab	91.8 ± 34.6ab	426.5 ± 23.5c	494.2 ± 48.9ac	16.7–4.4

[a] Values are means ± standard error. Means followed by a different letter are significantly different ($p < 0.05$).

[b] A fixed ratio of (below ground NPP) / (Total NPP) = 0.5 was applied to estimate below ground NPP for *Menyanthes trifoliata* and 0.88 for *Carex utriculata*. For other vascular plants, the estimated below ground NPP includes only fine roots, with some range was considered. For the *Menyanthes trifoliata* pool, the *Carex utriculata – Sphagnum lindbergii* depression and the *Rhynchospora alba – Sphagnum tenellum* lawn, the ratio of 0.33 was used for the lowest estimation, and 0.70 for the highest estimation. For the *Racomitrium lanuginosum* hummock and the *Sphagnum austinii* hummock, the ratio of 0.38 was used for the lowest estimation, and 0.70 for the highest estimation.

[c] Ratio of above- and below-ground NPP.

TABLE 4.5 *Mass loss (decomposition) of* Sphagnum fuscum *litter from litter bags incubated at 10 cm below ground surface for 1 year (adapted from Asada et al., 2004)*

Study site	Site series[a]	Community[b]	Mass loss(%)[c]
Port Simpson	–[d]	P1	17.4 ± 2.3ab (6)
	–	P2	16.0 ± 1.1ab (20)
	–	P3	17.7 ± 0.6ab (14)
	–	P4	15.7 ± 1.2ab (6)
Diana Lake	04	D1	16.5 ± 1.1ab (6)
	01	D2	12.9 ± 1.3b (10)
	11	D3	16.2 ± 1.2ab (9)
	12	D4	16.5 ± 1.3ab (13)
	32	D5	23.7 ± 0.9a (3)
	32	D6	14.4 ± 1.5b (12)
	32	D7	17.1 ± 0.6ab (6)
	32	D8	21.0 ± 0.3ab (4)
	32	D9	13.5 ± 0.4ab (2)

[a] Site series 32: Non-forested slope – blanket bog; site series; 12: Shore pine – yellow cedar – *Sphagnum;* site series; 11: Western redcedar – yellow cedar – Goldthread; site series; 01: Western redcedar – Western hemlock – Salal; and site series 04: Western hemlock – Sitka spruce – Lanky moss.

[b] P1 = *Sphagnum angustifolium* community; P2 = *Polytrichum formosum – Sphagnum girgensohnii* community; P3 = *Cornus canadensis – Hylocomium splendens* community; P4 = *Sphagnum pacificum* community. D1–D5 are micro-communities in the non-forested slope–blanket bog site series and D6–D9 are communities at site series level. D1 = *Menyanthes trifoliata* pool; D2 = *Carex utriculata–Sphagnum lindbergii* depression; D3 = *Rhynchospora alba – Sphagnum tenellum* lawn; D4 = *Racomitrium lanuginosum* hummock; and D5 = *Sphagnum austinii* hummock.

[c] Values are means ± standard error; number of plots appears in parenthesis. Means followed by a different letter are significantly different ($p < 0.05$).

[d] Mainly dominated by 01 before clearcutting and mounding.

greater in the aerobic zone above the water table than in the anaerobic zone below the water table, with intermediate decomposition rates in the zone of water table fluctuation (Asada and Warner 2005). The rate of mass loss was slightly higher in this study than in comparable studies in other areas.

The long-term peat accumulation rate on the peatland is likely lower than in continental peatlands. From a series of C^{14}-dated peat cores, Turunen and Turunen (2003) found that the average vertical peat accumulation rate (over the past ± 8000 years) at Diana Lake was 0.15 mm/yr, with a range of 0.09–0.24 mm/yr. This accumulation rate is lower than that found in other studies in continental North America, which ranged from 0.39 to 1.05 mm/yr, as well as southeast Alaska, which ranged from 0.18 to 1.05 mm/yr (Gorham et al. 2003).

Recent peat accumulation rates at the Diana Lake bogs, measured using ^{210}Pb techniques, are 1.4–3.2 mm/yr over the past 65–70 years and 0.9–1.9 mm/yr over the past 200 years, indicating that carbon has accumulated under normal climate conditions in the recent past (Turunen and Turunen 2003; Asada and Warner 2005).

Researchers concluded from the studies at Diana Lake that hypermaritime peatlands rank lower than other continental peatlands in overall NPP and carbon accumulation. Although some hypermaritime peatland microcommunities (e.g., *S. fuscum* and *S. austinii* hummocks) have relatively high NPP and peat accumulation rates, others (e.g., *Rhynchospora alba – S. tenellum* lawns) are low in productivity. Relatively high decomposition rates in hypermaritime peatlands tend to offset production, even in the most productive sphagnum communities, thus yielding relatively low overall rates of peat and carbon accumulation (Malmer and Wallen 1993; Asada and Warner 2005). Near surface peat carbon balance studies indicate that both the *S. austinii* and *R. alba – S. tenellum* communities are carbon sinks, although the carbon balance in the less-productive *R. alba – S. tenellum* communities could be close to equilibrium (Asada and Warner 2005).

4.4 Vegetation Types and their Dynamics: Discussion

The vegetation of the Diana Lake area is characteristic of that on the north coast; similar plant communities are described within the Biogeoclimatic Ecosystem Classification (BEC) system (Banner et al. 1993). The driving environmental factor in determining these communities is moisture. This is exemplified in the study area by the importance of drainage and water table depth. For example, the mounding treatment at the Port Simpson site altered the moisture regime in the mounded area through the formation of pits adjacent to most mounds. These pits (many had standing water) were subsequently invaded by sphagnum mosses that were not present or less common in the area before harvesting occurred. These mosses are still expanding in extent and may have the potential to paludify portions of adjacent upland sites.

The sphagnum moss species examined had different growth responses to climatic variation, mostly related to their habitat and growth form. Species that form hummocks had lower linear growth rates and less seasonal variation in growth, than species that grew in wetter conditions, such as lawns and hollows. Differences in moisture regime between hummocks and hollows may explain these differences. Because hollows are wet most of the year, species in this habitat type can use water more easily and therefore undergo less stress than hummock-forming species. During dry periods when the water level drops, however, species in hollows cannot retain water for growth because of their loose growth form. Conversely, hummock-forming species, with their denser growth form, can retain water even in dry periods because of their superior water-holding capacity. The moisture content in hummocks, therefore, is lower but more constant than that in hollows. This allows hummock-forming species to grow during dry periods as well as during wetter periods, although the growth rate would be slow. These differences in growth pattern between hummock-forming and hollow or lawn-forming species agree with some previous findings (Moore 1989; Gerdol 1995).

Even if adequate moisture is present, substantial growth will not occur if the temperature is too low. This hypothesis was supported by higher correlations between growth and the climatic index than precipitation alone for most of the species studied (Table 4.1). Previous studies have observed this relationship for only a few species. For example, Lindholm (1990) determined that the minimum temperature for growth of *Sphagnum fuscum* was 0°C; above this temperature, growth was controlled by water availability. Gerdol (1996) observed the same trend for *S. magellanicum*. Vitt (1989) confirmed the importance of precipitation above temperature thresholds with the finding that yearly growth variation of *Racomitrium microcarpon* was related to precipitation during the growing season.

Sphagnum species and the other two moss species exhibit different temperature thresholds for growth. Our preliminary results on the relationship between moss growth and the climatic index indicate that the temperature threshold for sphagnum growth is about 0°C; for *R. lanuginosum* and *P. schreberi*, it is about 5°C. These low thresholds suggest potential winter growth, especially for sphagnum, in this mild hypermaritime region. Winter growth appears considerable, as is evident for sphagnum in other hyperoceanic regions (Hulme and Blyth 1982).

Over the 8 years following forest harvesting at Port Simpson, sphagnum moss growth has progressed as follows:

- Clearcutting alone has not yet promoted significant colonization or advancement of sphagnum.
- Mounding after clearcutting created hollows in which pools formed or where the water table was very shallow.
- The exposed peat provided a competition-free substrate for pioneer sphagnum moss species to invade.
- The water chemistry gradient set up by sphagnum along the mound–hollow transition may further facilitate sphagnum moss growth and discourage the growth of other plant species.

Paludification at this site is evident by:

- The presence of *S. pacificum* and *S. angustifolium*, which were presumably almost absent before harvesting. These species are increasing in area and volume, especially in the hollows. They are thought of as pioneer species, which later provide conditions appropriate for the establishment of other sphagnum species.
- The rapid expansion of *S. girgensohnii* patches that presumably help to create lawns on which other bog sphagnum species (e.g., *S. capillifolium*) can establish.
- The vertical growth rate of sphagnum at the Port Simpson site is about the same or faster than that at the Diana Lake site.
- The decomposition rates at the Port Simpson site are similar to, or slightly slower than, those at the Diana Lake site.

We are not clear how paludification will proceed at the Port Simpson site in relation to forest regeneration; we will continue site monitoring indefinitely. Three developmental pathways are possible for these sites:

1. Tree regeneration doesn't proceed well, sphagnum continues to expand, and species composition changes through succession with expansion of fen or bog communities in the cutover area.

2. Tree regeneration proceeds moderately well on the mounds; because of shading the expansion of bog-type sphagnum stops and shade-tolerant forest-type sphagnum becomes dominant. The area becomes a wet lower-productivity forest (similar to pre-harvest condition).
3. Regeneration proceeds well on the mounds and, because of increasing interception and evapotranspiration, the water table drops. Sphagnum species are unable to persist or expand, and an upland forest results with higher tree productivity than the pre-harvest stand.

4.5 Soil Ecology

4.5.1 Soil/bedrock relationships Mineral soils on the north coast are typically colluvial or saprolitic in origin, most often developing in shallow veneers over bedrock. The most common bedrock types on the north and central coast are:

- granodiorite (including quartz diorite and diorite),
- gneissic diorite, and
- schist or gneiss, with some localized areas of limestone (Figure 4.7).

These bedrock types have differences in weathering rates and mineral composition (Table 4.6) resulting in a range of physical and chemical soil properties. Granodiorite is an igneous intrusive rock with a high content of quartz, feldspar, and some biotite. It is a relatively hard rock that weathers slowly, and the mineral soils derived from it are generally shallow and nutrient poor. Gneissic diorite is an igneous intrusive rock with less quartz and more biotite, garnet, and some hornblende. Gneissic diorite is slightly banded, or foliated, suggesting that partial metamorphism has taken place. In this case, the layering results from additional pressure, temperature, or chemical reactions applied to the rock. Gneissic diorite is scattered throughout the CWHvh2 (Figure 2.1) and data suggest that this rock type is associated with slightly more productive sites compared with the granodiorites. Schist is a strongly foliated, or

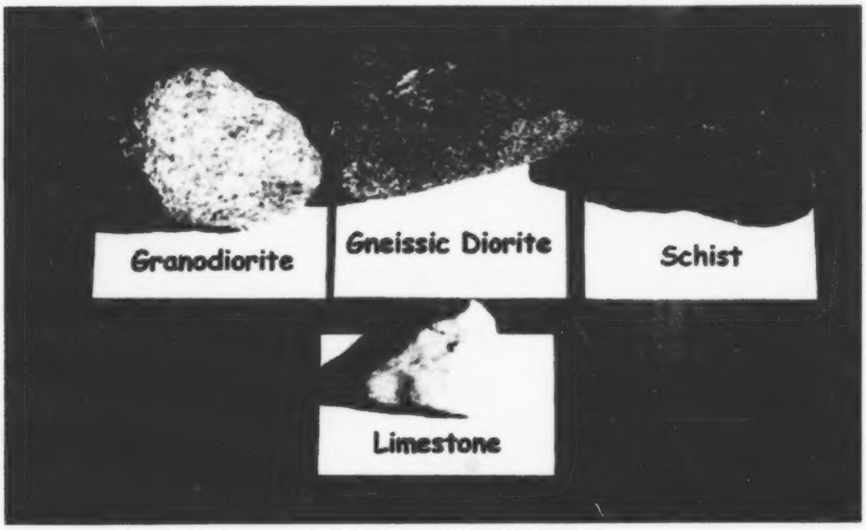


FIGURE 4.7 *Four common bedrock types found on the north and central coast of British Columbia.*

TABLE 4.6 *Total chemical concentrations for bedrock types*[a] *(adapted from Kranabetter and Banner, 2000)*

Bedrock type	P (g/kg)	S (g/kg)	Ca (g/kg)	Mg (g/kg)	K (g/kg)	Mo (mg/kg)	Cu (mg/kg)	Fe (g/kg)	Mn (g/kg)	Zn (mg/kg)	Co (mg/kg)
Granodiorite	1.07	0.33	29.5	14.8	33.8	< 2	4.8	37.1	0.7	50.2	5.3
	(0.3)	(0.2)	(4.4)	(3.7)	(11.8)		(0.75)	(7.5)	(0.1)	(5.3)	(1.39)
Gneissic diorite	2.12	2.51	48.8	24.6	23.8	< 2	30.8	63.0	1.1	100.5	10.2
	(0.2)	(2.4)	(6.8)	(7.1)	(6.9)		(23.5)	(13.6)	(0.2)	(37.9)	(2.95)
Schist	2.15	0.45	87.6	33.9	11.8	3.7	18.3	84.2	1.0	42.0	9.7
	(0.2)	(0.2)	(40.1)	(7.2)	(2.3)	(2.5)	(7.3)	(26.1)	(0.4)	(10.0)	(4.16)
Limestone	0.20	2.83	520.6	9.4	0.4	< 2	< 1	2.6	0.2	8.7	< 1
	(0.1)	(0.1)	(15)	(3.8)	(0.2)			(1.3)	(0.1)	(2.6)	

a Values in parentheses are standard errors.

layered, metamorphic rock, intermediate between slate and gneiss with a high content of mica or mica-like minerals. This rock type is relatively soft and weathers quickly to create mineral soil and provide nutrients for plant growth. As a result, some of the highest forest productivity on the outer coast is associated with schist bedrock, especially when it occurs in combination with limestone. Limestone is largely made up of calcium carbonate; in the CWHvh2, it is limited to small pockets scattered along the coast. Limestone weathers by solution and gives rise to generally rich, productive forests (e.g., CWHvh2/05, Western redcedar – Sitka spruce – Swordfern), and often unique plant communities (Kranabetter and Banner 2000).

We examined the relationship between bedrock type and mineral and organic soil depth using information from the Prince Rupert Forest Region ecological database, which includes 165 ecosystem plots collected from sites throughout the CWHvh2. These plots were collected over the last 25 years to develop an ecosystem classification, and thus were not specifically designed to determine relationships between bedrock and soil. Soil horizon thicknesses were combined for both the organic and mineral layers to arrive at the total depth for each of these soil layers. The depth of mineral soil must be interpreted carefully, however, because in nearly one-half of the plots bedrock was not reached in the soil pit; in these cases, the measured mineral soil depth will partially depend on the thickness of the overlying organic layer.

Tables 4.7 and 4.8 summarize soil depth related to site series and bedrock type. Table 4.7 illustrates the trends in mineral and organic soil depth among site series; organic horizon depth tends to increase and mineral soil depth tends to decrease from the productive upland forests (CWHvh2/04) to the bog forests (CWHvh2/11). These trends were generally not statistically significant ($p < 0.05$), except for the thinner organic horizon depth on the CWHvh2/04 sites series compared with the CWHvh2/01 and /11. Within both the CWHvh2/01 and /04 site series, a trend exists in mineral soil depth as it relates to bedrock geology, with the deepest mineral soils occurring on the metamorphic (schist) bedrock (Table 4.8). Again, the data are highly variable and this trend was not statistically significant. A trend in organic soil depth with bedrock type within site series was less apparent, indicating slightly shallower organic horizons on metamorphic rock within the CWHvh2/04 site series only.

The nutrient differences between soils derived from the various rock types are largely due to varying amounts of phosphorus (P), sulphur (S), magnesium (Mg), and potassium (K) (Table 4.9) (Kranabetter and Banner 2000). For example, schist-derived mineral soils are higher in P, S,

TABLE 4.7 *Mean organic and mineral soil depths for CWHvh2 site series on the north and central coastal of British Columbia*

Site series	*n*	Organic soil depth (cm)[a]	*n*	Mineral soil depth (cm)[a]
11	29	37.0a (3.5)	24	22.5a (4.6)
01	60	31.7a (2.5)	57	30.9a (3.0)
04	76	20.4b (2.2)	76	36.8a (2.6)

a Values in parentheses are standard errors. Means followed by a different letter are significantly different ($p < 0.05$).

TABLE 4.8 *Mean organic and mineral soil depths for CWHvh2/01 and CWHvh2/04 site series by bedrock type on the north and central coast of British Columbia*

Site series	Bedrock type	*n*	Organic soil depth (cm)[a]	*n*	Mineral soil depth (cm)[a]
01	Granitic	37	34.3 (3.7)	34	24.9 (3.7)
	Gneissic diorite	15	23.1 (5.9)	15	41.4 (5.6)
	Schist	7	35.1 (8.6)	7	37.6 (8.2)
04	Granitic	35	21.4 (2.3)	35	37.2 (4.1)
	Gneissic diorite	25	19.7 (2.8)	25	32.0 (4.9)
	Schist	14	17.9 (3.7)	14	45.4 (6.5)

a Values in parentheses are standard errors. Means within a site series were not significantly different ($p < 0.05$).

TABLE 4.9 *Average chemical properties of mineral soils (0–20 cm), well-drained sites only [a] (adapted from Kranabetter and Banner, 2000)*

Bedrock-derived soil	Total N (g/kg)	Total P (g/kg)	Total S (g/kg)	C:N ratio	C:P ratio	C:S ratio	Min.-N (mg/kg)	Avail. P (mg/kg)	Exch. Ca (cmol/kg)	Exch. K (cmol/kg)	Exch. Mg (cmol/kg)	pH (H_2O)
Granodiorite	1.8	0.23	0.22	29.1	220[a]	284a	14.6a	5.49	0.67	0.049a	0.19a	4.47
	(0.3)	(0.21)	(0.05)	(1.1)	(14.9)	(21.4)	(1.6)	(0.7)	(0.06)	(0.006)	(0.02)	(0.03)
Gneissic diorite	2.4	0.35	0.34	26.6	169ab	195ab	18.9a	8.78	0.70	0.050a	0.22a	4.49
	(0.8)	(0.83)	(0.18)	(1.5)	(13.6)	(11.7)	(3.0)	(2.6)	(0.14)	(0.008)	(0.04)	(0.05)
Schist	2.3	0.41	0.33	23.6	134b	170b	45.0b	8.79	1.64	0.109b	0.49b	4.64
	(0.3)	(0.47)	(0.04)	(1.0)	(9.8)	(12.0)	(7.1)	(1.6)	(0.26)	(0.010)	(0.04)	(0.10)

a $n = 3$ for each bedrock type. Values in parentheses are standard errors. Values followed by a different letter are significantly different ($p < 0.05$).

Mg, and K than mineral soils derived from other bedrock types. These nutrients on their own can influence site productivity, but they can also lead to higher nitrogen (N) availability (measured as mineralizable N), a nutrient fundamental to plant growth. At the other end of the spectrum, soils derived from granodiorite are low in nutrient elements, while soils from gneissic diorite tend to be intermediate between schist and granodiorite.

The scarcity of glacial till on the north coast has significant implications for forest productivity. Glacial till is typically composed of a mixture of ground up rocks of varied mineralogy. It has high surface area, and good potential for root access, balanced nutrient content, and weatherability. Soils derived from bedrock that has weathered *in situ*, such as those on the north coast, are generally less balanced in their nutrient content and limited by the specific chemical and physical properties of the rock.

Where roots have access to rock surfaces, recent studies have demonstrated the capacity for root and mycorrhizae exudates such as organic acids to weather rocks and take up nutrients directly (Jongmans et al. 1997; Bormann et al. 1998). Root and mycorrhizae access may be extremely limited, however, on hard plutonic rocks because of the lack of fractures and low surface area. Where deep, wet organic horizons develop, they can also prevent access to the underlying weathered bedrock. On the more easily weathered and fractured metamorphic rock, root access is much better, but compared with glacial till, even this relatively nutrient-rich bedrock is less balanced and more subject to single nutrient deficiencies. These rocks have already undergone significant weathering, which has removed many of the most weatherable minerals.

The implications to forest management of this lack of glacial till on the north coast are significant, especially because it is the harder, resistant, and relatively nutrient-poor plutonic rocks that dominate the coast. Low rates of nutrient inputs to these systems via slow weathering and atmospheric deposition (rain, clouds, fog) mean that longer rotations will be required to re-establish merchantable forests in these areas, and fertilization treatments may also be necessary. Initial results from the HyP^3 studies suggest that the inherent forest productivity, as well as the potential to improve productivity through site treatments, is considerably higher in the areas dominated by metamorphic bedrock.

4.5.2 Soil disturbance and nutrient availability Though bedrock plays a significant part in determining nutrient availability and site productivity, disturbance history also plays a role. On the north coast, high forest productivity is generally associated with sites on steep slopes with good soil drainage and aeration, and often a history of natural disturbance by landslide or windthrow events. These disturbance events tend to mix mineral and organic soil layers, slowing the buildup of surface organic material, and improving nutrient availability (Bormann et al. 1995). In contrast, the lower-productivity western redcedar-dominated sites (CWHvh2/01 and /11) found on the gentle terrain of the Hecate Lowlands are imperfectly to poorly drained, and have much lower levels of available nutrients (Kranabetter et al. 2003). These sites lack disturbances, which allows deep layers of organic matter to accumulate. If disturbance events are rare or small, deep accumulations of surface organic matter result. On these sites, the depth of the organic layers prevents tree roots from gaining access to mineral soil. In some cases, mineral horizons are absent (Folisols) and forest floors play an increasingly important role in nutrient supply (Chapter 2, section 2.3).

4.5.3 Organic matter and nutrient availability Edmonds et al. (1989) suggested that nutrient availability from forest floors depends on the turnover rate and nutrient content of the organic matter. These factors are examined in two HyP^3 soil studies. Kranabetter and Banner (2000) compared chemical properties and lab microbial respiration rates (as an indicator of decomposition rates) in forest floor samples collected from productive, freely drained forest sites occurring on contrasting bedrock types (granodiorite, gneissic diorite, schist, and limestone). Kranabetter (B.C. Ministry of Forests 2004, unpublished data) compared the same forest floor properties among CWHvh2/01, /04, and /11 site series, and then manipulated water content of forest floor samples to see whether moisture content influenced decomposition rates (measured as microbial respiration in the lab).

Although organic matter turnover rates were expected to be higher on the richer bedrock types, on the more productive site series, and in the least-saturated forest floors, this was not apparent in the lab respiration results. Microbial respiration was variable in the incubated forest floor samples taken from the top 15 cm of soil profiles, but broadly similar on freely drained sites across contrasting bedrock types (Figure 4.8a). Across site series either at field moisture content, or at higher or lower moisture levels, no statistically significant trends were evident (Figure 4.9). Surprisingly, some samples representing the wettest forest floors from the poorest site series had the highest respiration rates.

Lower C:N and C:P ratios on the richer schist-derived soils (Figure 4.8b), and on the most productive site series in both old-growth and second-growth conditions (Figure 4.10), suggest that organic matter quality is better characterized by nutrient content than by turnover rates. The results imply that the decline in tree productivity across site series more strongly reflects a decline in the available nutrient content of partially decomposed organic matter (the end product of decomposition) than lower decomposition rates.

These laboratory respiration experiments do not completely mimic field processes, however. The CWHvh2/01 and /11 site series could experience periods of complete saturation and reduced decomposition compared to well-drained sites, especially at depths deeper than 15 cm, as measured in this study. The tests conducted in this experiment were limited to carbon cycling (CO_2 release). It is possible that the wetter soil conditions could lead to differences in faunal and microbial activity that affect N rather than C mineralization and this may result in differences in organic matter "quality." The P content of litter and soil has been reported to control N mineralization in upland and organic soils (Purchase 1974; Munevar and Wollum 1977; Pastor et al. 1984; White and Reddy 2000; Carlyle and Nambiar 2001), and is generally recognized as

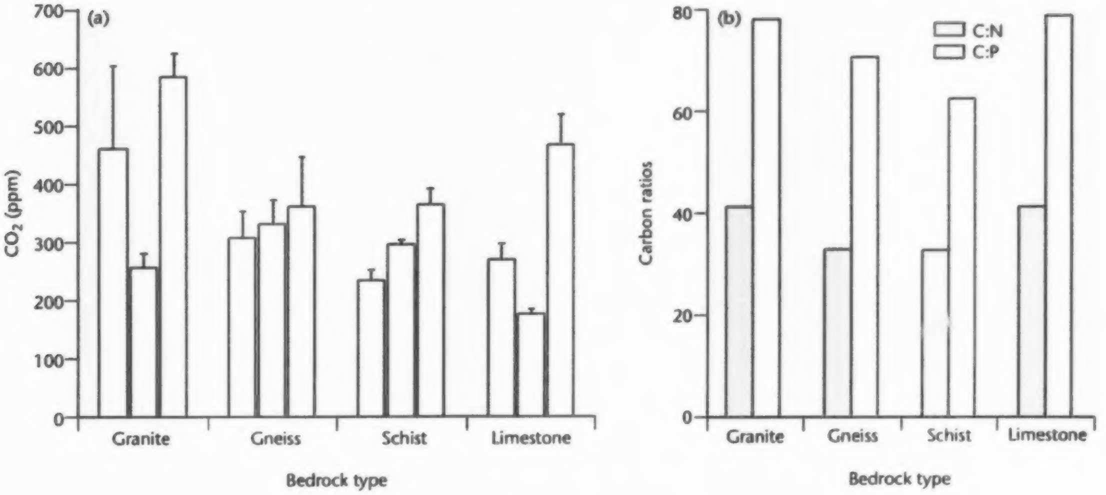


FIGURE 4.8 *Comparisons of microbial respiration rates and chemical properties: (a) a comparison of forest floor (0–10 cm) respiration rates (laboratory incubation) across well-drained bedrock-derived soils (3 samples per bedrock type); (b) C:N and C:P ratios of upper forest floors across well-drained, bedrock-derived soils (adapted from Kranabetter and Banner, 2000).*

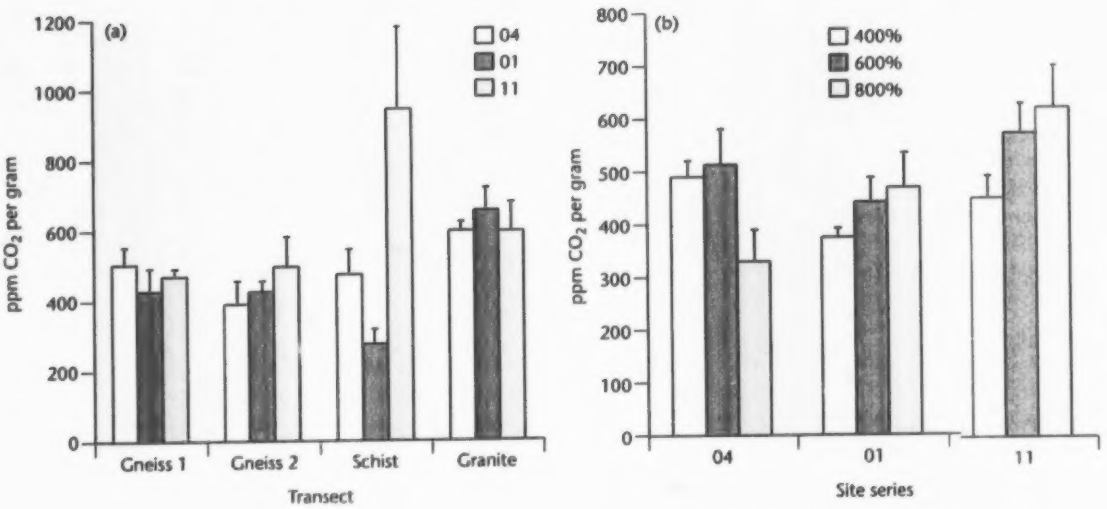


FIGURE 4.9 *Comparisons of microbial respiration rates and moisture content: (a) forest floor respiration rates (laboratory incubation) across site series at the appropriate field moisture content (400% for the 04, 600% for the 01, and 800% for the 11); (b) forest floor respiration (laboratory incubation) across moisture contents for the CWHvh2/04, /01, and /11 site series.*

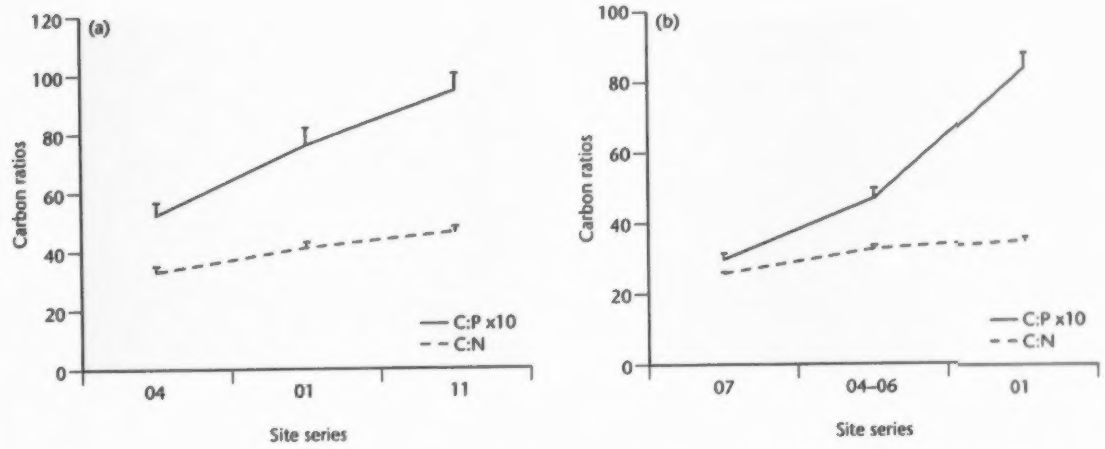


FIGURE 4.10 *Changes in C:N and C:P ratios across CWHvh2 site series in (a) old-growth and (b) second-growth stands. Site series numbers as per Figure 2.7.*

exerting a large influence on N cycling and fixation (Chapin et al. 1978; Cole and Heil 1981; Vitousek and Howarth 1991). Low supplies of P, due to lower-quality parent materials or reduced rooting in mineral soils beneath deep surface organic layers, may limit N availability and this may in turn result in a decline in forest productivity. Ecosystem decline resulting from the long-term absence of catastrophic disturbance has been linked to P limitations in a recent study of contrasting chronosequences in tropical, temperate, and boreal zones (Wardle et al. 2004).

Early results from operational trials suggest that long-term improvements in tree productivity require mixing of organic matter with mineral soil horizons to improve soil aeration and to increase the uptake and cycling of P, N and S. This treatment is thought to mimic the beneficial consequences of natural disturbances, such as colluvial mixing or blowdown events, which are associated with sites that support more productive stands in these coastal forests (Kranabetter and Banner 2000).

Mixing and mounding site treatments are being tested at operational trials at the Port Simpson and Oona River study areas (Chapter 6, sections 6.2 and 6.3).

4.5.4 Tree growth and foliar nutrition

Tree growth and nutrition in second-growth plantations (approximately 20 years of age) were compared across a range of sites (e.g., CWHvh2/ 01, /04, /05, /06, /07, and /11 site series) occurring over various bedrock types from granodiorite to schist (Kranabetter et al. 2003). Foliar analysis was used to infer which nutrient elements were at adequate levels and which limited growth (van den Driessche 1974; Ballard and Carter 1986; Walker and Gessel 1991). To examine relationships between foliar nutrition and growth, foliar analysis was carried out on sample trees from which height and increment measurements were taken. To assess plant response to nutrient limitations, nutrient **retranslocation** between current and older foliage was also examined. This useful method is based on the theory that trees on nutrient-poor sites will retranslocate, or move, nutrients from older foliage to younger foliage to compensate for deficiencies in available soil nutrients (Nambiar and Fife 1991).

Foliar chemistry, rather than soil chemistry, was used to ascertain nutrient availability on these sites because studies show that soil chemistry is of limited value in determining nutrient availability. Soil analysis measures the supply of elements potentially available, whereas foliar analysis provides an index of the amount actually taken up by the trees (Ballard and Carter 1986). In addition, soil analysis is often difficult to interpret when forest soil depth and composition are extremely variable, as is often the case on the outer coast of British Columbia.

Many foliar nutrient concentrations (e.g., N, P, K, S) had a positive relationship with leader increment. As leader increment continued to increase, these nutrients did not appear to "plateau" at the adequate concentrations previously determined in greenhouse growth tests by Ballard and Carter (1986) (Figures 4.11, 4.12, and 4.13). Some foliar cation concentrations (e.g., Ca, Mg) showed little relationship to growth. Trees on the better growing sites (well-drained schist soils and seepage sites; CWHvh2/04, /05, /06, and /07 site series) in this study exhibit the highest productivity that has been found in the hypermaritime zone. Typical foliar nutrient concentrations for each tree species from these more productive sites (Table 4.10) were compared with published reports of adequate foliar nutrients. Western hemlock and Sitka spruce had nearly adequate concentrations of N (1.45–2.2%) and P (0.25–0.35%) on productive sites (Radwan and Harrington 1986; Weetman et al. 1989a, 1989b; Walker and Gessel 1991). In general, the cations and micronutrients on productive sites were also at adequate concentrations, as

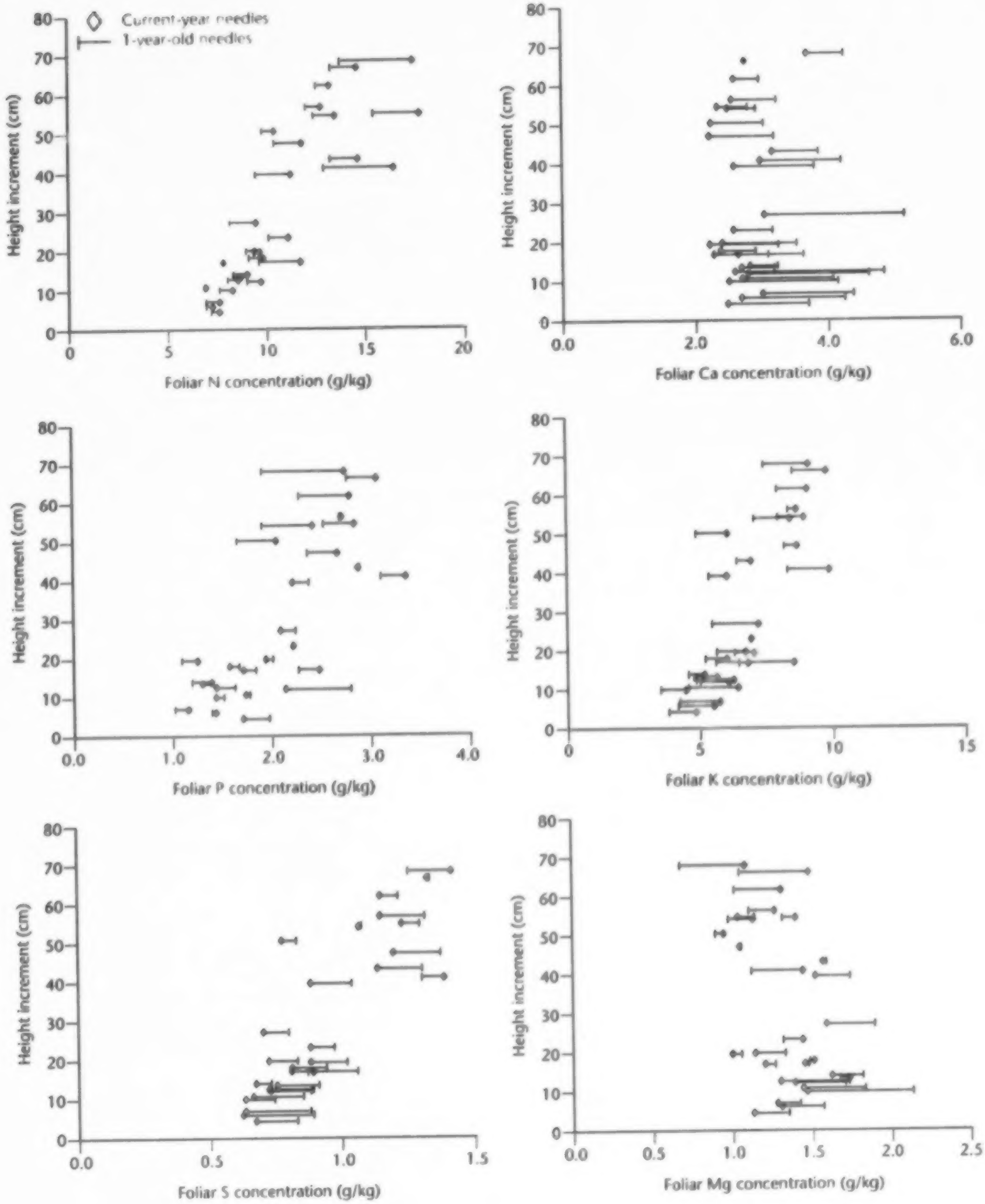


FIGURE 4.11 *Western hemlock nutrient concentrations for current-year needles and 1-year-old needles across height increment (adapted from Kranabetter et al., 2003).*

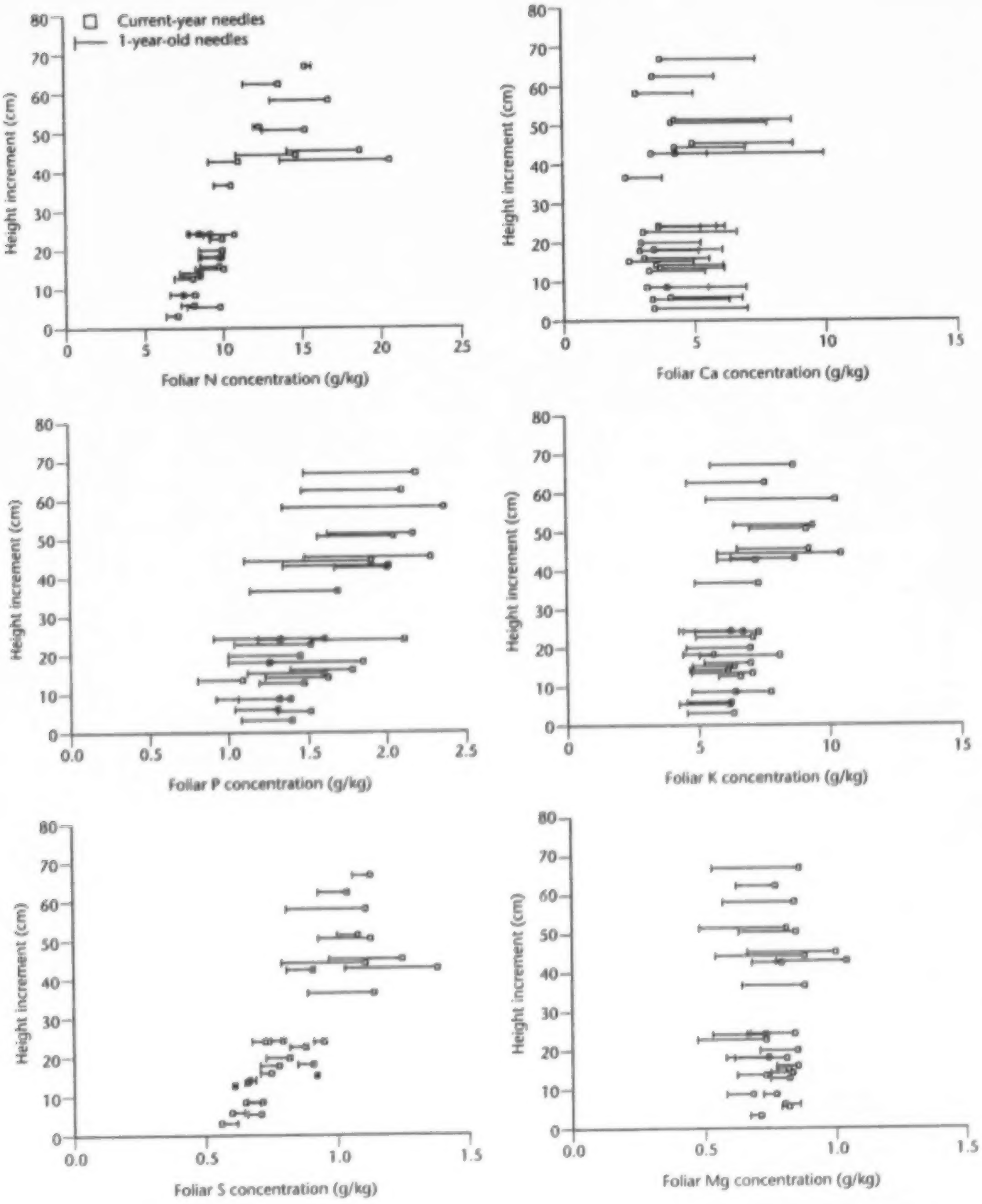


FIGURE 4.12 *Sitka spruce foliar nutrient concentrations for current-year needles and 1-year-old needles across height increment (adapted from Kranabetter et al., 2003).*

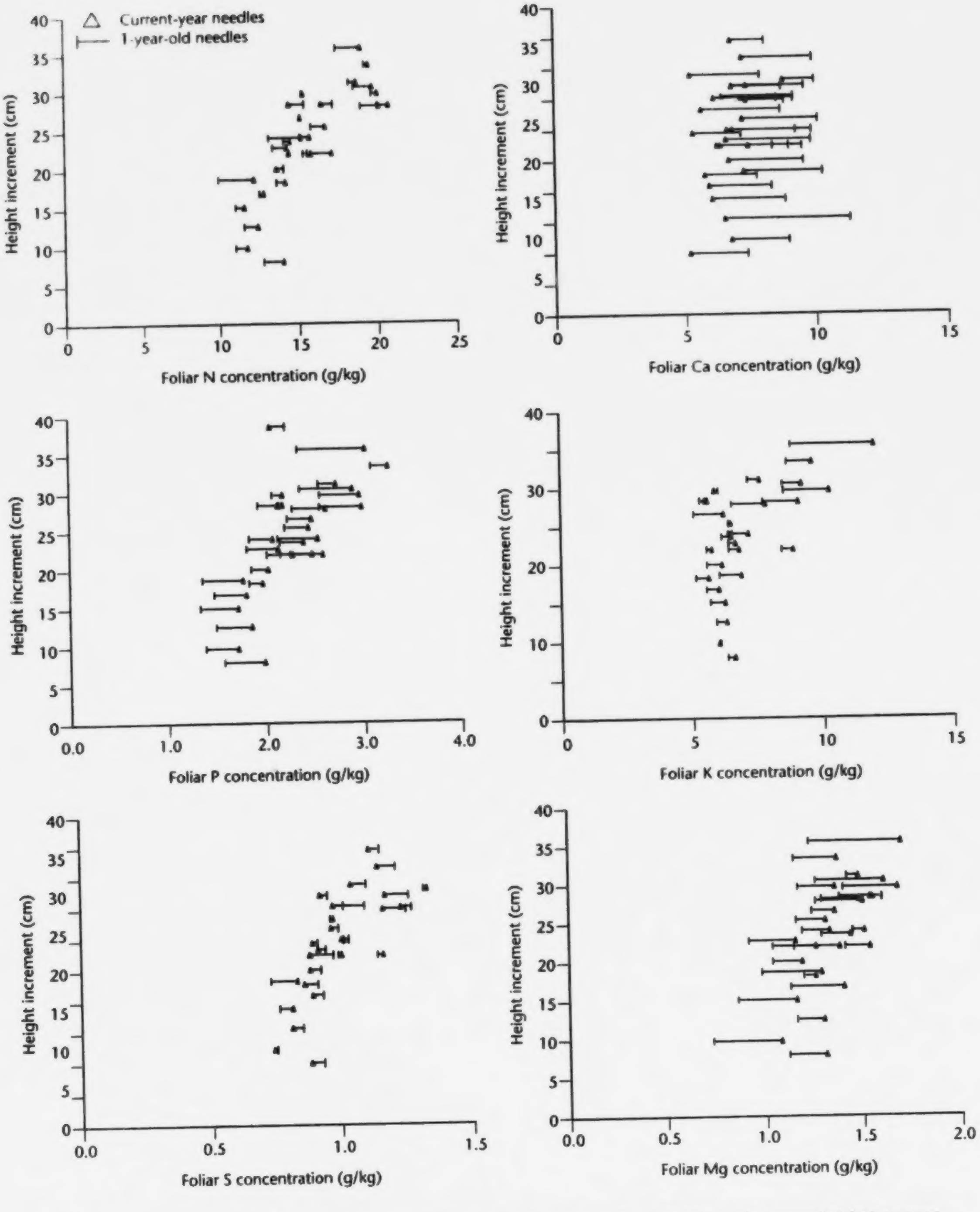


FIGURE 4.13 *Western redcedar foliar nutrient concentrations for current-year needles and older needles across height increment (adapted from Kranabetter et al., 2003).*

TABLE 4.10 *Foliar nutrient concentrations for western hemlock, Sitka spruce, and western redcedar on productive sites of north coast British Columbia (adapted from Kranabetter et al., 2003)*

	N	P	S	Mg	K	Ca	B	Cu	Fe	Mo	Mn	Zn
Species	(%)						(ppm)					
Western hemlock	1.45	0.28	0.12	0.120	0.90	0.25	15	3.0	35	0.02	1500	12
Sitka spruce	1.55	0.22	0.11	0.085	0.90	0.40	10	3.0	30	0.02	1000	25
Western redcedar	1.85	0.28	0.11	0.150	0.90	0.65	15	5.0	30	0.20	250	20

reported by Ballard and Carter (1986). The largest discrepancy between observed and adequate nutrient levels occurred with P in western redcedar (0.28% P compared to the suggested level of 0.16%). According to published standards, levels as high as 0.28% P occur more often in interior redcedar (Radwan and Harrington 1986). Such a large variation from the expected P concentration implies that the suggested level of 0.16% may underestimate the true P requirements for western redcedar on these sites.

All three tree species had strong positive correlations between average leader increment and foliar N, P, and S, along with secondary correlations for many cations or micronutrients. The generally positive, linear response of many foliar macro- and micronutrients made it difficult to infer specific growth limitations. It is unclear, for example, whether the availability of N, P, S, K, Mg, Cu, Fe, Mn, and Zn in soils changed across moisture and bedrock regimes, or whether the deficiencies of N or P simply limited the uptake of these other elements. The strong correlations between micronutrients such as Fe and Zn and leader increment were often species specific, an aspect that would be interesting to test further in field trials.

Retranslocation between new and older foliage was determined by comparing nutrient concentrations of current needles against the previous year. The largest difference in foliar nutrient concentrations generally occurred in more productive trees; nutrient concentrations on the most stressed sites showed generally more stability between years (Figures 4.11, 4.12, and 4.13). The slightly higher rate of S accumulation for western hemlock was the only difference in nutrient concentrations between new and older foliage that suggested a larger deficiency on poorer sites. On richer sites (CWHvh2/05 and /07 sites series), where N availability might be naturally quite high, the large decrease in S and Mg concentrations in older needles suggested Sitka spruce was limited by these elements. This is similar to the induced deficiencies that can sometimes occur when N fertilizer is applied (Brockley et al. 1992). Western hemlock also showed similar patterns of possible Mg retranslocation on seepage sites. Overall, the observed patterns of retranslocation are opposite from the pattern originally expected. Rather than finding greater retranslocation on nutrient-poor sites as a response to stress, greater movement of nutrients between old and new foliage was recorded on richer sites. These preliminary findings raise new questions concerning nutrient limitations to growth, especially on richer sites; further field tests with added nutrients would be needed to draw more complete conclusions.

Although vegetation competition or edaphic conditions posed no apparent difficulties in establishing trees on the CWHvh2/01 sites studied, the height increment results show considerable differences in growth rates from well-drained to imperfectly drained sites. Increment growth on the CWHvh2/01 sites averaged 42% less for western hemlock, 56% less for Sitka spruce, and 32% less for western redcedar compared with the better-drained sites. Bedrock also had an influence on growth increment. The CWHvh2/01 sites on granodiorite and gneissic diorite bedrock showed the lowest growth rates (Table 4.11), suggesting that these sites are at the lowest threshold of operability. The CWHvh2/01 schist sites, however, had more acceptable rates of tree growth, and are thus considered to have higher potential for forestry operations.

The height increment results for western redcedar, Sitka spruce, and western hemlock illustrate some important aspects of the autecology of these species. Western redcedar, although relatively slow growing, had the smallest decrease in height increment across the site series, and thus seems better adapted to the poorer soils over the long term. Considering ecological suitability as well as species value, western redcedar should be chosen as the preferred species on most CWHvh2/01 sites. Sitka spruce exhibited by far the best growth on the good sites, but showed dramatically reduced growth on the poor sites, especially on granodiorite. Species selection guidelines reflect the higher nutrient and soil drainage demands of this species (Banner et al. 1993), and thus spruce is the least acceptable tree species on CWHvh2/01 sites. The autecological characteristics of western hemlock are intermediate between those of western redcedar and Sitka spruce. This species, therefore, could be considered an acceptable or preferred species on CWHvh2/01 sites, depending on specific management objectives and other factors (e.g., mistletoe risk). See Chapter 5 (section 5.3 and Table 5.1) for a summary of tree species productivity in the CWHvh2, and Chapter 7 for a further discussion of species selection guidelines.

The growth and foliar responses observed largely confirm the lower productivity of the CWHvh2/01 site series, especially on poorer bedrock types, and provided further evidence that N and P availability declines along the productivity gradient. Operational trials are under way at Port Simpson and Oona River to test whether the availability of N and other nutrients is enhanced by mixing mineral soil with forest floors, which simulates blowdown events, or through additions of P fertilizer (see Chapter 6). The growth and nutrition results from these current studies should allow us to better evaluate the potential, and investment required, to improve site productivity on CWHvh2/01

TABLE 4.11 *Average height increment (cm) for each tree species by soil moisture regime and bedrock type[a] (adapted from Kranabetter et al., 2003)*

	Bedrock type		
Site series	**Granodiorite**	**Gneissic**	**Schist**
Western hemlock			
01 CwHw[b] Salal	14.0 (1.6)	5.6 (0.9)	38.0 (5.2)
04–06 Site Series[c]	26.6 (4.6)	15.5 (1.8)	57.4 (3.8)
07 CwSs[b]-Devil's club	37.1 (5.4)	17.6 (1.9)	58.4 (5.6)
Sitka spruce			
01 CwHw Salal	5.8 (1.0)	9.1 (1.4)	21.7 (2.2)
04–06 Site Series	14.0 (2.0)	21.3 (2.6)	49.1 (2.0)
07 CwSs-Devil's club	52.4 (5.0)	26.8 (3.6)	51.4 (4.1)
Western redcedar			
01 CwHw Salal	15.0 (1.8)	13.2 (1.2)	23.6 (1.5)
04–06 Site Series	21.4 (1.8)	26.1 (2.3)	28.5 (2.0)
07 CwSs-Devil's club	26.3 (2.7)	25.8 (2.4)	31.1 (1.5)

a $n = 3$ per combination. Values in parentheses are standard errors.
b Cw = western redcedar, Hw = western hemlock, Ss = Sitka spruce.
c See Figure 2.7 for site series names.

sites. Although the lowest-productivity sites on poorer bedrock may initially seem to have a greater need for productivity-improving site treatments, fertilization (rather than soil mixing) may be the only option on these sites because very little mineral soil is associated with the harder igneous rocks; the soils are most often Folisols, which consist of deep LFH (forest floor horizons) layers with a thin layer (less than 10 cm) of mineral soil over rock. Metamorphic (schist) sites have the greatest potential for improving nutrient availability through soil-mixing treatments because mineral soils are often much deeper and higher in nutrient cation content. Although our existing operational trials are both located on metamorphic bedrock, we plan to establish trials on poorer bedrock types to better define operability limits.

4.6 Model of Ecosystem Development and Productivity in the CWHvh2

From the studies of ecosystem patterns, processes, and productivity outlined above, a simple model of ecosystem development in the CWHvh2 has emerged (Figure 4.14). In this model, three main factors operate in combination to drive ecosystem development and productivity in this hypermaritime environment:

1. bedrock geology
2. soil drainage
3. disturbance history

Although these same factors influence ecosystem development to some degree in most other terrestrial environments, their influence is especially dramatic in the CWHvh2. This model relates directly to the edatopic grid typically used to portray BEC site series (Figure 2.7); soil moisture and nutrient regime (and thus site series) are largely determined by the interaction of bedrock geology, soil drainage, and disturbance history.

The scarcity of glacial till in this coastal environment highlights the importance of

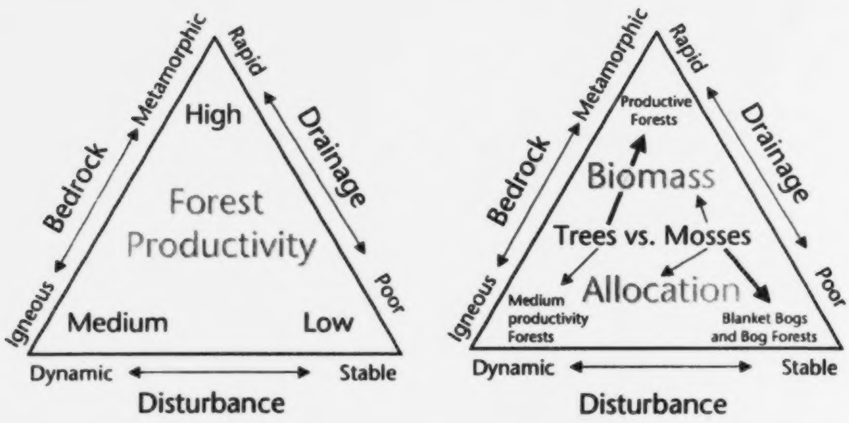


FIGURE 4.14 *Simplified model of ecosystem development and forest productivity in the CWHvh2. The version on the left emphasizes the role of bedrock geology, soil drainage, and disturbance history in controlling tree productivity; the version on the right emphasizes how these same environmental factors determine the relative allocation of tree versus moss biomass in north-coast ecosystems.*

bedrock geology. Most soils develop directly from the weathering of bedrock or colluvial material. This contrasts with many other areas where a mantle of glacial till of mixed lithology masks the influence of bedrock. In addition, sharp contrasts in bedrock type occur on the outer coast, from the hard, slowly weathering granodiorites with relatively low amounts of available nutrient elements, to the much softer, faster weathering metamorphic rocks and limestone with more nutrient-rich lithologies. These different bedrock types manifest themselves in dramatic differences in plant communities and forest productivity.

Excess soil water is the rule in this hypermaritime environment, and subtle variations in slope or internal soil drainage result in significant differences in forest productivity. In contrast to the majority of other subzones in the province (where moisture deficits are common), the most freely drained sites in the CWHvh2 are the most productive sites for trees. Even these "drier" sites are fresh to moist in absolute terms, but as long as soil water is dynamic rather than stagnant, then tree productivity will remain moderate to high.

The tendency for organic matter to accumulate on sites that have not been disturbed by windthrow, landslides, or fluvial disturbances for hundreds (or thousands) of years is also dramatic in the CWHvh2. As soil organic matter accumulates, soils become wetter and tree roots become more confined to surface organic horizons. Although the nutrient capital in these organic horizons is considerable, nutrient availability is relatively low because of the wet, acidic conditions and low rates of nitrogen mineralization. Better-drained sites that often have a history of natural disturbance, especially where soil organic and mineral horizons are mixed, exhibit higher forest productivity.

Although models are inherently simplistic, on the majority of sites on the outer coast, ecosystem development and forest productivity can be explained by the above three factors working in combination. The model presented in Figure 4.14 can also be used to guide forest management investments and activities, and to help define and understand the limits of operability in the CWHvh2. For example, marginally productive sites occurring on metamorphic rock will likely exhibit higher second-growth productivity following harvesting and site treatments, compared with a similar site on granodiorite bedrock.

Note that two variations of the model are presented—one emphasizing forest productivity and one emphasizing biomass allocation. As indicated by the soil ecology, moss productivity, and succession studies, a switch in biomass allocation from trees to mosses (and other understorey vegetation) occurs as sites progress along the (slow) trajectory of organic matter accumulation and declining tree productivity. Bogs and bog forests are often referred to as "low productivity." They are, however, highly productive if one considers the annual rates of total biomass accumulation measured in these ecosystems (see section 4.3.3).

5.1 Introduction and Approach

The classification and inventory component of the HyP³ Project serves as the link between the hydrology and ecosystem process components, and the application of results across the north coast. The project has used the Biogeoclimatic Ecosystem Classification (BEC) system (Pojar et al. 1987) as the framework to make ecologically based forest management recommendations. BEC uses the site series to classify forests for management purposes. Ecosystem classification is invaluable for choosing appropriate sites for in-depth studies, and also for extrapolating the results to other similar sites throughout the north coast.

We conducted sampling in old-growth and second-growth forests to collect baseline information on tree growth and site productivity throughout the range of forested site series in the CWHvh2. Forest harvesting in the CWHvh2 has largely been limited to the higher-productivity forest types. For these sites, we have regeneration and site index data from second-growth and old-growth forests, which provide information on regeneration and productivity under full-light and partial-light conditions. On the lower-productivity sites (CWHvh2/01, /11, and /12), few second-growth stands exist; therefore, to establish baseline growth patterns and rates for these sites, we combined the limited site index and "years to breast height" sampling data available for second-growth stands with stem analysis of trees in old-growth stands.

At each of the HyP³ study sites, timber cruising was carried out to quantify stand structure, species composition, and gross and merchantable volume. Several forest mensuration attributes are summarized from these data for each of the CWHvh2 site series studied.

A review of rare, or otherwise threatened or imperiled ecosystems of the CWHvh2 is presented to examine any potential impacts on these ecosystems that might result from expanding forestry operations into the lower-productivity forest types.

A predictive ecosystem mapping (PEM) model was developed for the outer coast. The resulting maps identify the site series most likely associated with each forest cover polygon. These maps help to establish the extent and location of potentially operable low-productivity cedar–hemlock forest types. Site series productivity data can also be combined with these maps to aid in growth and yield analysis for the TSA.

5.2 Site Series Description

The BEC system classifies sites within each subzone into a range of site series depending on relative soil moisture and relative soil nutrient regimes (see Figure 2.7). Within the CWHvh2, the HyP³ Project is mostly concerned with lower-productivity forests with mesic and wetter moisture regimes, and medium to poor nutrient regimes on the edatopic grid; the site series representing these forest types are: CWHvh2/01 (Western Redcedar – Western Hemlock – Salal) and CWHvh2/11 (Western Redcedar – Yellow-cedar – Goldthread) (Banner et al. 1993). To draw the necessary comparisons between forest productivity and soil moisture–nutrient relationships, study transects include other common site series within the CWHvh2.

Depending on the soil development and the site series, three phases of site series are recognized in this subzone (Banner et al. 1993).

1. Mineral phase: occurs on sites with colluvial, morainal, weathered bedrock, or fluvial deposits (> 10 cm).
2. Lithic phase: occurs on sites with an organic veneer over thin (< 10 cm)

mineral soil over bedrock or boulders.

3. Peaty phase: occurs on sites with a peaty veneer or blanket (> 10 cm) over bedrock.

5.2.1 Zonal forests Zonal forests (CWHvh2/01; Western redcedar – Western hemlock – Salal) have relatively low tree stature, open canopies, and well-developed shrub layers compared with productive forests (see Figure 2.3 and Figure 5.1). These forests are found on a range of sites from upper to lower slopes. The soils are usually imperfectly drained Podzols and Folisols with relatively deep organic horizons in comparison to the underlying mineral horizons. The open scrubby forests are dominated by western redcedar, yellow-cedar, and western hemlock, with shore pine and mountain hemlock abundant in some locations. Forests on the CWHvh2/01 site series often have low productivity compared to zonal sites found in other CWH subzones (Banner et al. 1993).

5.2.2 Bog forests Bog forests (CWHvh2/11; Western redcedar – Yellow-cedar – Goldthread) are very extensive in the CWHvh2, especially on the Hecate Lowlands. These very open and scrubby "forests" are found on a variety of slope positions, but mostly on gentle terrain; however, on poor bedrock these forests can extend up considerable slopes in some areas. Soils are organic veneers or blankets over bedrock or saprolite. The tree species are usually yellow-cedar and western redcedar with some shore pine interspersed (Figure 2.4 and Figure 5.2). Forests on the CWHvh2/11 site series are of lower productivity than those of the CWHvh2/01 (Banner et al. 1993).

5.2.3 Bog woodlands and open bog ecosystems Bog woodlands (CWHvh2/12; Shore pine – Yellow-cedar – Sphagnum) and open bogs (CWHvh2/32; slope–blanket bog) are very common on the outer coast (Figures 2.5 and 2.6; Figures 5.3 and 5.4). These woodland and bog complexes are typical of the subdued terrain of the Hecate Lowlands where organic soils predominate. A sparse tree cover of less than

FIGURE 5.1 *Zonal forest (CWHvh2/01), Oona River.*

FIGURE 5.2 *Bog forest (CWHvh2/11), Diana Lake.*

FIGURE 5.3 *Bog woodland (CWHvh2/12), Diana Lake.*

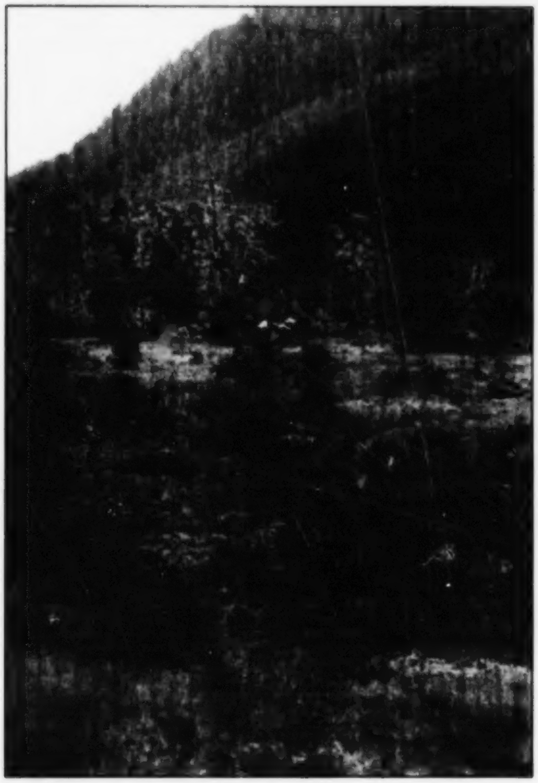


FIGURE 5.4 *Open bog (CWHvh2/32), Diana Lake.*

10% is typical of the woodlands; scattered, very scrubby trees occur in the open bogs. The main tree species is shore pine, with some yellow-cedar and western redcedar (Banner et al. 1993). Based on detailed vegetation sampling, Asada (2003b) identified five sub-communites within the CWHvh2/32 open bogs (see section 4.3.2).

5.2.4 Productive forests Productive non-floodplain forests are represented by the CWHvh2/04 (Western hemlock – Sitka spruce – Lanky moss), CWHvh2/05 (Western redcedar – Sitka spruce – Swordfern), CWHvh2/06 (Western redcedar – Sitka spruce – Foamflower), and CWHvh2/07 (Western redcedar – Sitka spruce – Devil's club) site series. These forests are most commonly located on steep colluvial slopes, but are also found on inactive coarse fluvium with free drainage, toe slope seepage sites, deep morainal soils, and shallow Folisols. CWHvh2/05 is restricted, almost exclusively, to areas of metamorphic or limestone bedrock. Depending on disturbance history and chance, varying mixtures of western hemlock, western redcedar, Sitka spruce, and amabilis fir dominate these sites (Figure 2.2 and Figure 5.5). Compared with zonal sites, these site series occur on better-drained or more nutrient-rich soils, which results in higher-productivity forests (Banner et al. 1993).

FIGURE 5.5 *Productive upland forest (CWHvh2/06), Port Edward.*

5.2.5 Floodplain forests Productive forests found on floodplains are site series CWHvh2/08 (Sitka spruce – Lily-of-the-valley), CWHvh2/09 (Sitka spruce – Trisetum), and CWHvh2/10 (Red alder – Lily-of-the-valley) (Figure 5.6). The three different site series are distinguished by the height and frequency of flooding of the high, middle, and low benches, respectively. The low benches (CWHvh2/10) have Regosolic soils, with a progression to Brunisolic and Podzolic soils occurring on the less frequently flooded middle and high benches (CWHvh2/09 and /08). Sitka spruce, western hemlock, and western redcedar dominate the CWHvh2/08 site series; the CWHvh2/09 site series is dominated by Sitka spruce, while the CWHvh2/10 site series is dominated by red alder (Banner et al. 1993).

FIGURE 5.6 *Productive spruce stand on a CWHvh2/08 site, Barnard Creek, Princess Royal Island.*

5.2.6 Swamp forests Swamp forests (CWHvh2/13; Western redcedar – Sitka spruce – Skunk cabbage) are found in poorly drained areas with mineral seepage.

These forests are localized in lower slope positions and level areas sometimes over fluvial deposits, with organic blankets and veneers. The mineral seepage results in a richer nutrient regime and better forest productivity than in the bog forests and bog woodlands (CWHvh2/11 and /12), which have a similar moisture regime. These forests are most often dominated by western redcedar, less commonly by Sitka spruce, with a vigorous and consistent cover of skunk cabbage characterizing the understorey (Figure 5.7) (Banner et al. 1993).

5.2.7 Drier forest and scrub Drier forests (CWHvh2/03; Western redcedar – Yellow-cedar – Salal) are uncommon, but do occur on some upper-slope and ridge-crest positions on Folisols over (mostly nutrient-poor) bedrock. Species composition, stand structure, and productivity are all very similar to the CWHvh2/01 site series (Western redcedar – Western Hemlock – Salal). On the most exposed, dry rocky knolls and outcrops, the Shore pine – Yellow-cedar – Racomitrium (CWHvh2/02; Figure 5.8) site series occurs. These shrubby, open habitats with very thin soils typically occur on rock outcrops interspersed throughout open bogs on the Hecate Lowlands (Banner et al. 1993).

5.3 Site Productivity

In British Columbia, the vast majority of forest land is covered with old-growth stands ("old" depends on the zone). The B.C. Forest Service used data derived from inventory plots located in old stands to establish a baseline measure of site quality or productivity, commonly referred to as "site index." Site index (SI) is an estimate of potential tree height growth on a site over a fixed period of time. In British Columbia, we use SI_{50}, or total tree height at a breast height age of 50 years. The productivity of a site largely determines how quickly trees grow and thus volume production and merchantable rotation age. In recent years, extensive site index sampling of second-growth stands (< 120 years, Figure 5.9) indicates that site productivity estimates from the old-growth forest cover inventory underestimate actual site productivity of regenerated stands (Table 5.1). Second-growth forests tend to grow

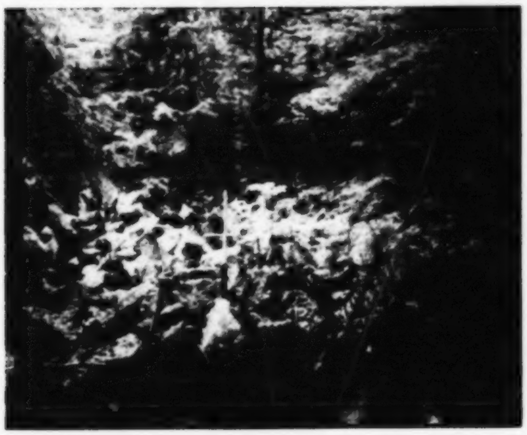


FIGURE 5.7 *Swamp forest (CWHvh2/13), Diana Lake.*

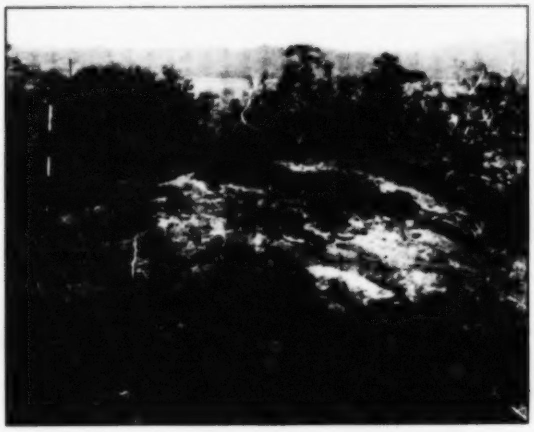


FIGURE 5.8 *Dry, windswept rock outcrop (CWHvh2/02), McCauley Island.*

faster than projected by the inventory-based site index estimates derived from old-growth stands (Nigh 1998; Nussbaum 1998; Olivotto and Meidinger 2001).

Tree growth and thus site index is strongly influenced by ecological site factors such as soil moisture and nutrient regime. A significant relationship exists between site index and BEC site series. The **Site Index–Biogeoclimatic Ecosystem Classification** Project (SIBEC) produced a database that summarizes site index estimates (from second-growth field data) by site series for coniferous tree species in British Columbia (B.C. Ministry of Forests 2003). These data are collected from second-growth stands in which trees have regenerated under open conditions, and therefore the resulting site index estimates are believed to better represent growth potential on these sites following a disturbance. On a sample of five map sheets from the north coast, for example, current forest cover information shows that more than 50% of the total land base has a SI_{50} of eight or less. Estimates of productivity for the same area using SIBEC estimates puts just 4% of the land base into this category (Olivotto and Meidinger 2001; see section 5.6 for a further discussion of ecosystem-based productivity and yield analysis). Although other factors will also determine operability, many areas on the north coast currently listed as inoperable may indeed be more productive than currently estimated by the forest inventory and therefore have some potential for sustainable forestry.

5.3.1 Site Index and Years to Breast Height The site index values presented in

FIGURE 5.9 *Second-growth CWHvh2 stand used for site index sampling, Khyex River.*

Table 5.1 summarize data collected over a large area of the north coast in the last 10 years. The data include information obtained from old-growth stem analysis plots from four locations, second-growth foliar nutrient plots from 14 locations, and SIBEC plots from 50 locations. These data show that estimates of site productivity from old-growth stands significantly underestimate second-growth site potential (e.g., western redcedar old growth, CWHvh2/01 site series; $SI_{50} = 3.9$ vs. second-growth $SI_{50} = 17.8$; old-growth years to breast height (BH) = 50 vs. second-growth years to BH = 7).

TABLE 5.1 *Old-growth and second-growth productivity data*[a] *for the CWHvh2, north coast of British Columbia. Site series numbers as per Figure 2.7 (see section 5.2 for site series descriptions)*

Old Growth, Mean Site Index[b]

Site series	Amabilis fir	Western redcedar	Mountain hemlock	Western hemlock	Shore pine	Sitka spruce	Yellow-cedar
01		3.9 (1.9–10.5)	3.0 (2.0–7.7)	2.7 (1.3–6.2)	4.8 (2.3–9.5)	4.7 (2.5–5.7)	4.0 (1.7–9.8)
04	2.9 (1.7–5.0)	5.2 (2.8–7.4)		3.2 (1.7–5.3)			
11		2.9 (2.0–4.5)	3.1 (2.3–3.9)	3.1 (1.4–5.3)	3.8 (1.8–7.1)		2.9 (1.7–5.5)
12		3.3 (2.5–4.5)	3.0 (2.2–5.5)	2.0 (1.9–2.1)	2.8 (1.8–3.7)		2.4 (1.7–3.5)

Old Growth, Mean Years to Breast Height[b]

Site series	Amabilis fir	Western redcedar	Mountain hemlock	Western hemlock	Shore pine	Sitka spruce	Yellow-cedar
01	58 (21–120)	50 (15–124)	69 (24–105)	65 (9–173)	59 (17–84)	67 (27–89)	45 (11–137)
04	70 (12–163)	37 (21–50)		61 (6–158)		34 (34–34)	
11		73 (32–137)	72 (37–105)	73 (40–159)	51 (31–70)		73 (32–158)
12		79 (37–184)	101 (38–178)	108 (63–172)	89 (39–174)		107 (45–361)

Second Growth, Mean Site Index[c]

Site series	Amabilis fir	Western redcedar	Mountain hemlock	Western hemlock	Shore pine	Sitka spruce	Yellow-cedar
01		17.8 (13.5–22.3)		18.0 (8.0–31.0)		16.6 (13.5–21.0)	
04	26.9 (14.9–35.4)	22.7 (17.0–34.3)		22.9 (10.0–33.5)		27.4 (19.5–40.8)	
05	31.7 (24.7–36.0)			28.3 (24.4–32.8)			
06	29.6 (18.2–34.7)	23.2 (18.9–26.6)		27.0 (21.0–32.8)		33.0 (23.1–42.4)	
07		21.7 (15.5–28.0)		21.9 (11.1–36.2)		29.3 (18.6–43.1)	

Second Growth, Mean Years to Breast Height[c]

Site series	Amabilis fir	Western redcedar	Mountain hemlock	Western hemlock	Shore pine	Sitka spruce	Yellow-cedar
01		7 (3–11)		6 (3–10)	5 (3–6)	6 (3–8)	
04	7 (5–12)	8 (5–12)		5 (3–9)		5 (4–8)	
05	6 (5–8)			5 (5–6)			
06	6 (5–11)	10 (9–10)		6 (5–7)		6 (4–7)	
07		10.0 (9–11)		6 (4–9)		6 (3–11)	

a Mean site index data: height (m) at 50 years (breast height age). Range of site index in parentheses.

b Values derived from HyP³ stem analysis plots.

c Values derived from HyP³ stem analysis samples and BC Forest Service SIBEC plots.

5.4 Forest Mensuration

To quantify and compare the volume and quality of timber across the spectrum of site series, timber cruises were done at three HyP^3 study sites (Diana Lake, Oona River, and Smith Island). Results presented in Table 5.2 are shown using a lower limit of both 7.5 and 17.5 cm DBH. Differences among the site series are most evident in volumes and **basal area**, with the CWHvh2/04 site series having the highest gross and net volume, the most basal area, and trees with the largest DBH. The CWHvh2/01 and /11 site series are progressively lower for all of these measures. Stems per hectare followed the opposite pattern with the CWHvh2/01 and /11 site series having higher densities than the CWHvh2/04 sites. The number of snags per hectare above 7.5 cm DBH was highest on the CWHvh2/11 site series, followed by the CWHvh2/01 and /04. Above 17.5 cm DBH, the CWHvh2/04 site series had the most snags followed by the CWHvh2/11 and /01. When compared to zonal sites in other CWH variants, the CWHvh2/01 site series contains the lowest volume per hectare and the highest number of snags per hectare (B.C. Ministry of Forests 2001).

Western redcedar contributes the most volume on the CWHvh2/01 and /11 site series, with lesser amounts contributed by western hemlock, yellow-cedar, and shore pine (minor amounts of Sitka spruce are found in the CWHvh2/01) (Figure 5.10). Western hemlock, western redcedar, and Sitka spruce, with some amabilis fir and minor amounts of yellow-cedar, dominate the CWHvh2/04 site series. Stems per hectare by species follow similar trends to volume, except for the CWHvh2/04, where relatively few stems of Sitka spruce and amabilis fir (these species are mostly restricted to the upper canopy layers) make up the volume for these sites (Figure 5.11).

The stems per hectare by diameter class curves all show a similar and typical reverse "J" shape (exponential distribution), with many small trees and fewer large trees. The slopes of the curves exhibit some differences, however, with the CWHvh2/11 and /01 site series showing steeper curves as a result of fewer large trees. Basal area diameter class distributions by site series show clear differences among sites. Basal area on the CWHvh2/11 site series is concentrated in the smaller diameter classes, with very little basal area above 55 cm diameter (Figure 5.12). On CWHvh2/01 site series, there is little basal area over the 100 cm diameter classes, and on the /04 site series, the curve ends at 110 cm. The peaks in basal area in the larger size classes on the CWHvh2/04 sites are produced by a few large trees.

The distribution of trees by height class clearly shows the differences among the site series with the CWHvh2/04 including more trees in the taller height classes than the CWHvh2/01 and /11 site series (Figure 5.13). Merchantable trees on the

TABLE 5.2 *Summary of average stand characteristics for the CWHvh2/11, /01, and /04 site series at the Diana Lake, Oona River, and Smith Island study site areas*

Site series	*n*	DBH[a] (cm)	Volume/ha (m^3) Gross	Volume/ha (m^3) Net	Basal area/ha (m^2)	Stems/ha	Snags/ha	Average DBH (cm)
11	21	7.5	188.7	133.4	38.0	787	399	28.7
		17.5	159.0	107.6	33.8	459	123	33.8
01	44	7.5	329.3	229.3	54.2	809	202	30.3
		17.5	298.4	202.9	50.4	457	107	37.9
04	11	7.5	508.1	398.7	60.6	760	152	35.8
		17.5	479.0	373.2	56.6	372	152	44.7

[a] Diameter at breast height values represent the lower diameter limit used in the cruise compilation. Site series numbers as per Figure 2.7.

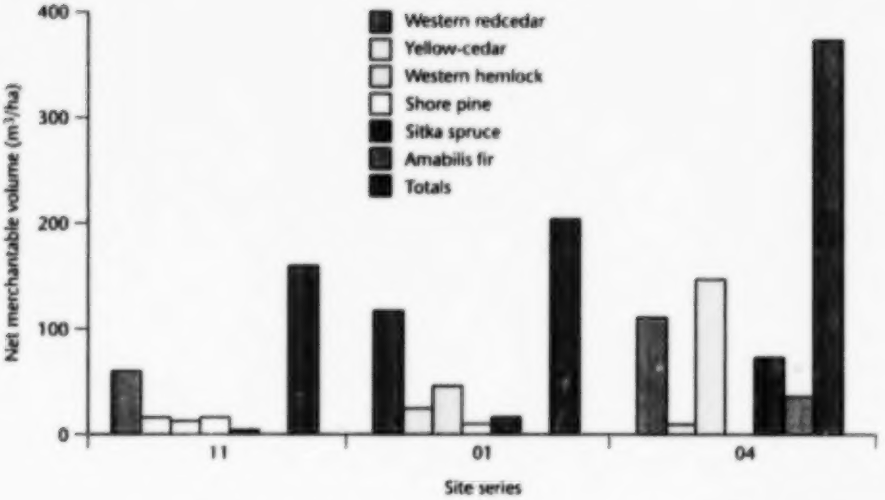


FIGURE 5.10 *Net merchantable volume per hectare (> 17.5 cm* DBH*) by site series and species at the Diana Lake, Oona River, and Smith Island study sites. Site series numbers as per Figure 2.7.*

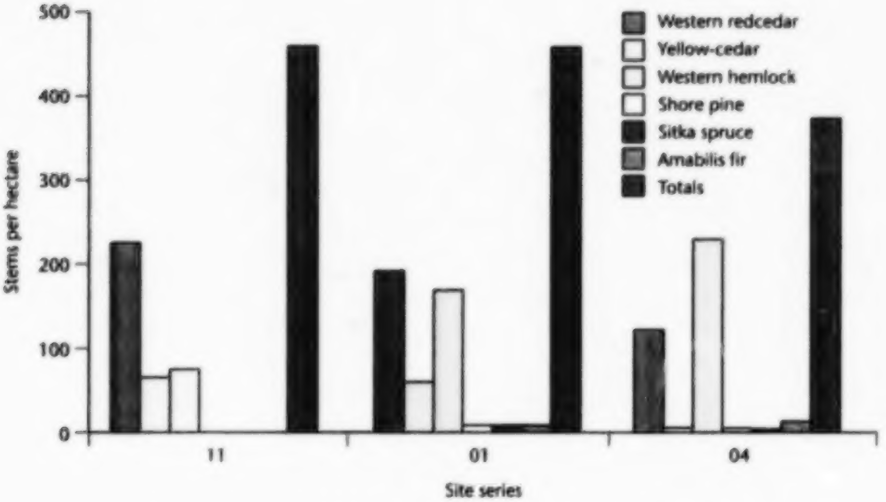
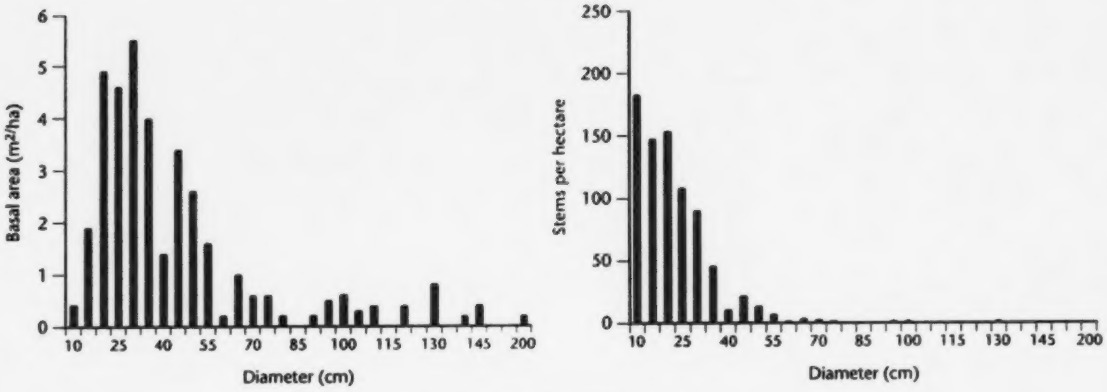
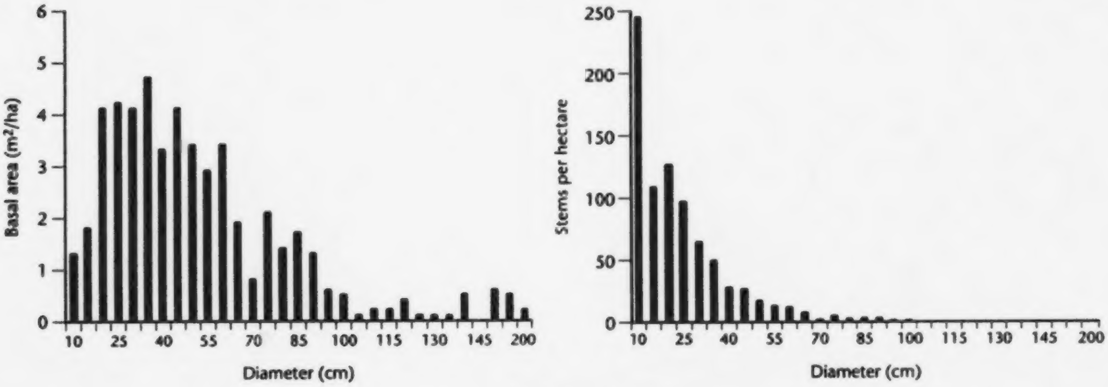


FIGURE 5.11 *Stems per hectare (> 17.5 cm* DBH*) by site series and species at the Diana Lake, Oona River, and Smith Island study sites. Site series numbers as per Figure 2.7.*

(a) CWHVh2/11



(b) CWHVh2/01



(c) CWHVh2/04

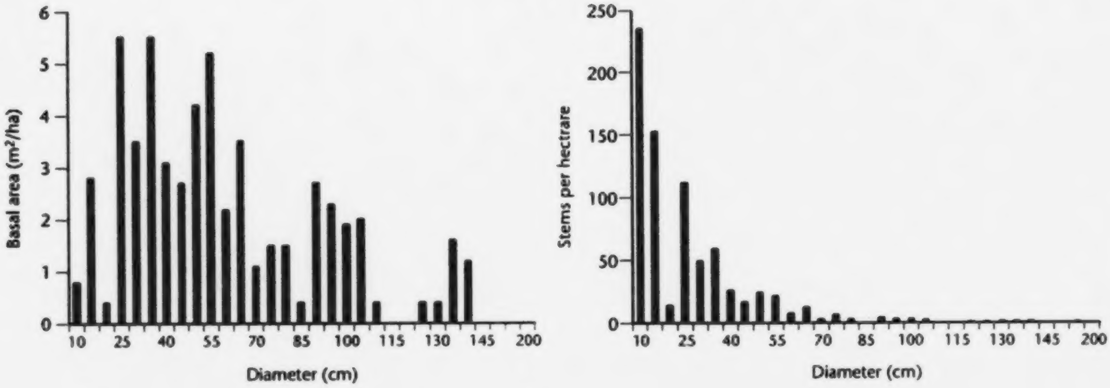


FIGURE 5.12 *Basal area and stems per hectare (≥7.5 cm DBH) in diameter classes at the Diana Lake, Oona River, and Smith Island study sites by site series: (a) CWHvh2/11; (b) CWHvh2/01; and (c) CWHvh2/04. Site series numbers as per* Figure 2.7.

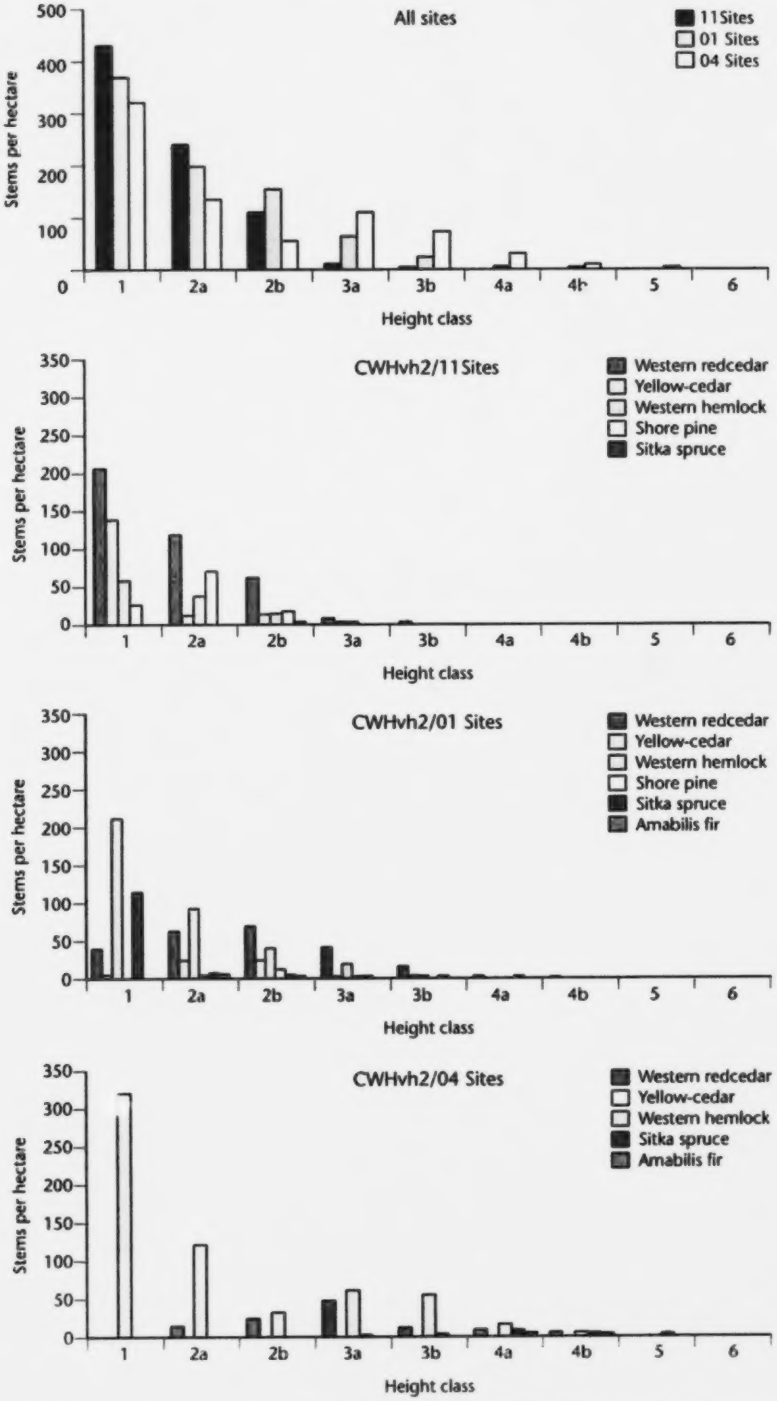


FIGURE 5.13 *Stems per hectare (≥7.5 cm DBH) in height classes by site series at all sites and by species at the Diana Lake, Oona River, and Smith Island study sites. Site series numbers as per Figure 2.7.*

CWHvh2/01 and /11 site series are concentrated in height class two, while CWHvh2/04 sites contain many merchantable trees in height class three and four. On all sites, there is a significant number of stems less than 7.5 cm DBH (e.g., advance regeneration) not tallied.

Species distributions in height classes (Table 5.3) vary greatly among site series. The CWHvh2/04 site series are dominated by hemlock in all height classes, but hemlock is especially dominant in the shorter height classes because of its high shade tolerance and ability to regenerate well on organic substrates. Hemlock also dominated the shorter height classes in the CWHvh2/01. Western redcedar was more prominent in the taller height classes on the CWHvh2/01 site series. On the CWHvh2/11 site series, western redcedar was dominant in all height classes, with yellow-cedar and shore pine also prominent in the shorter height classes. A summary of stand characteristics for all three site series at each site is presented in Tables 5.4, 5.5, and 5.6.

TABLE 5.3 *Tree heights used for height class designations*

Height class	Height range (m)
1	0.1–10.4
2a	10.5–14.9
2b	15.0–19.4
3a	19.5–23.9
3b	24.0–28.4
4a	28.5–32.9
4b	33.0–37.4
5	37.5–46.4
6	46.5–55.4

TABLE 5.4 *Summary of average stand characteristics for the CWHvh2/11 (Western redcedar – Yellow-cedar – Goldthread) site series at the three study sites*

Study site	*n*	DBH[a] (cm)	Volume/ha (m^3) Gross	Net	Basal area/ha (m^2)	Stems/ha	Snags/ha	Average DBH (cm)
Diana	4	7.5	165.0	120.0	33.3	546	374	27.9
		17.5	137.0	97.1	30.2	481	212	29.6
Oona	7	7.5	200.7	135.2	38.9	702	228	29.5
		17.5	179.1	116.3	36.0	353	61	38.5
Smith	10	7.5	189.7	137.4	39.4	944	528	28.5
		17.5	153.6	105.8	33.8	526	132	32.8

[a] Diameter at breast height (DBH) values represent the lower diameter limit used in the cruise compilation.

TABLE 5.5 *Summary of average stand characteristics for the CWHvh2/01 site series (Western redcedar – Western hemlock – Salal) at the three study sites*

Study site	*n*	DBH[a] (cm)	Volume/ha (m^3) Gross	Net	Basal area/ha (m^2)	Stems/ha	Snags/ha	Average DBH (cm)
Diana	8	7.5	429.0	288.1	69.8	1532	267	25.9
		17.5	375.0	242.3	61.9	618	108	34.7
Oona	22	7.5	331.5	235.0	50.5	574	98	36.1
		17.5	309.1	215.6	48.5	412	84.1	41.3
Smith	14	7.5	268.7	186.5	51.0	684	330	29.5
		17.5	238.9	161.7	47.4	437	143	36.3

[a] Diameter at breast height (DBH) values represent the lower diameter limit used in the cruise compilation.

TABLE 5.6 *Summary of stand characteristics for the CWHvh2/04 site series (Western hemlock – Sitka spruce – Lanky moss) at the three study sites*

Study site	*n*	DBH[a] (cm)	Volume/ha (m^3)		Basal area/ha (m^2)	Stems/ha	Snags/ha	Average DBH (cm)
			Gross	Net				
Diana	2	7.5	592.0	457.4	55.1	189	29	63.3
		17.5	586.0	453.0	55.1	189	29	63.3
Oona	4	7.5	453.8	359.3	49.0	438	48	37.9
		17.5	429.9	338.7	47.0	361	48	43.5
Smith	5	7.5	517.8	406.7	72.0	1246	621	31.7
		17.5	475.3	368.9	64.8	469	271	42.0

[a] Diameter at breast height (DBH) values represent the lower diameter limit used in the cruise compilation.

5.5 Biodiversity Considerations

As the HyP³ Project was analyzing the potential of harvesting in previously inoperable forests, the biodiversity implications of including these forests in the operable land base were investigated. This was done at the ecosystem, plant community, and species levels.

5.5.1 Red- and blue-listed ecosystems

Over 200 rare ecosystems in British Columbia are listed with the Conservation Data Centre (CDC) in Victoria. Many of these ecosystems are in the "old" structural stage of commercially valuable forests, or in mature forest and grassland ecosystems targeted for agricultural and urban development, especially in the southern one-third of the province.

A red-listed ecosystem is considered by the CDC as "imperiled provincially because of extreme rarity or because of some factor(s) making it especially vulnerable to extirpation or extinction." A red-listed ecosystem typically has fewer than 20 high-quality occurrences within the province. A blue-listed ecosystem may have from 21 to 100 occurrences, or is considered vulnerable to either large-scale disturbance or small-scale, but chronic, human-caused disturbance. Both red- and blue-listed ecosystems can be either naturally rare, or depleted and rare because of human activities.

Currently, the mainland portion of the Very Wet Hypermaritime Coastal Western Hemlock subzone (CWHvh2) contains 11 red- and blue-listed ecosystems (Table 5.7). These forests fall into two groups:

1. inland forests mostly on floodplains, fans, and colluvial slopes; and
2. forests that occur in salt-spray zones along windward shores or in brackish shoreline habitats.

Operational implementation of the HyP³ project's research findings does not, for the most part, pose significant or serious risks to these forest ecosystems. Harvesting activities in the forests targeted by the HyP³ Project, however, could impinge on rare forest types if:

- the stands targeted for harvesting are accessed via roads built through rare forest types;
- the higher-productivity stands representing red- or blue-listed ecosystems are used to economically justify harvesting of the lower-productivity cedar–hemlock forests occurring adjacent to them; or
- camp facilities or log-sorting and booming activities damage the rare forest types.

5.5.2 Other rare or threatened ecosystems

Several additional rare, sensitive, or threatened ecosystems occur in the CWHvh2 that are presently not listed with the CDC. These ecosystems are either not listed because of incomplete inventories, or because the CDC-listed ecosystems use BEC as a framework; many rare ecosystems have not been properly classified

TABLE 5.7 *Red- and blue-listed ecosystems of the hypermaritime mainland coast of British Columbia (adapted from B.C. Conservation Data Centre, 2004)*

Scientific name	Common name	Typical situation	Biogeoclimatic site unit	Provincial rank[a]	Provincial list
Group 1. Inland forests mostly on floodplains and alluvium/colluvium					
Tsuga heterophylla – Picea sitchensis – Rhytidiadelphus loreus	Western hemlock – Sitka spruce – Lanky moss	Alluvial/colluvial; inactive coarse fluvium	CWHvh2/04	S3	Blue
Thuja plicata – Picea sitchensis – Polystichum munitum	Western redcedar – Sitka spruce – Sword fern	Alluvial/colluvial; limestone and metamorphics	CWHvh2/05	S2S3	Blue
Thuja plicata – Picea sitchensis – Oplopanax horridus Very Wet Hypermaritime 2	Western redcedar – Sitka spruce – Devil's club Very Wet Hypermaritime 2	Alluvial/colluvial forest	CWHvh2/07	S3	Blue
Picea sitchensis – Maianthemum dilatatum Wet Hypermaritime 1	Sitka spruce – False lily-of-the-valley Wet Hypermaritime 1	High bench floodplain	CWHvh2/08	S2	Red
Picea sitchensis – Trisetum canescens	Sitka spruce – Trisetum	Middle bench floodplain	CWHvh2/09	S2	Red
Alnus rubra – Maianthemum dilatatum	Red alder – False lily-of-the-valley	Low bench floodplain	CWHvh2/10	S3	Blue
Thuja plicata/Picea sitchensis – Lysichitum americanum	Western redcedar – Sitka spruce - Skunk cabbage	Swamps on lower slopes and depressions	CWHvh2/13	S3	Blue
Group 2. Sea-spray / Shoreline forests					
Picea sitchensis – Kindbergia oregana	Sitka spruce – Kindbergia	Spray zone	CWHvh2/15	S3	Blue
Picea sitchensis – Calamagrostis nutkaensis	Sitka spruce – Reedgrass	Spray zone	CWHvh2/16	S3	Blue
Picea sitchensis – Polystichum munitum	Sitka spruce – Sword fern	Marine terraces	CWHvh2/17	S3	Blue
Picea sitchensis – Malus fusca	Sitka spruce – Pacific crab apple	Estuaries, brackish sloughs	CWHvh2/19	S3	Blue

[a] Provincial ranks. S1 = critically imperilled; S2 = imperilled; S3 = vulnerable; S4 = apparently secure; and S5 = secure.

within the BEC framework, or they have specific attributes, such as bedrock geology, which make them special cases within a given site series.

Forested ecosystems Although yellow-cedar is common in the CWHvh2, moderately productive old-growth stands of yellow-cedar, with healthy trees of good form in height class four and five, are rare (Figure 5.14). They typically occur at mid-elevations (250–400 m) and harvesting (generally helicopter logging) has occurred in many of them. A moderately productive old-growth forest with good amounts of both yellow-cedar and western redcedar, including veterans, was identified at Stair Creek on Douglas Channel in the early 1990s. Ecosystems represented included CWHvh2/01, /03, /04, /05, and /06. This area was proposed as an ecological reserve in 1992, and is still a valid candidate for protection.

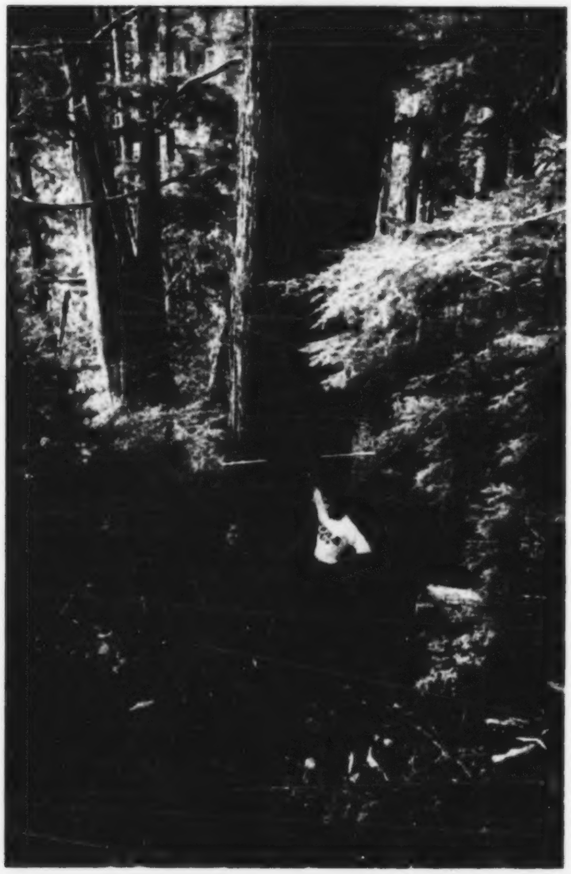


FIGURE 5.14 *Productive yellow-cedar stand on Mount Genevieve, Haida Gwaii/Queen Charlotte Islands.*

Yellow-cedar decline (i.e., the death of mature yellow-cedar trees) over considerable areas of southeast Alaska has been recognized as an ecological and management issue for many years (Hennon and Shaw 1997) Although various factors are implicated, including poor drainage and climate change (linked to early spring freezing injury), the causal agents remain unclear and continue to be studied. Some north coast stands located at 300–400 m elevations have recently been observed to have symptoms of yellow-cedar decline (P. Hennon, U.S. Department of Agriculture, Juneau, Alaska, pers. comm., Dec. 2004).

Forests on postglacial volcanic deposits are another category of regionally rare ecosystem. Strikingly productive forests of western hemlock, amabilis fir, western redcedar, and Sitka spruce occur on volcanic cones at Lake Island and Kitasu Hill (Swindle Island), with deep well-drained soils of ash and other unconsolidated material. Somewhat similar forests occur on deep tephra soils at Crow Lagoon, a caldera near the mouth of Khutzeymateen Inlet, and a sister caldera further upslope. All of these areas have been affected by harvesting.

Karst landforms with gentle (but freely drained) topography can support productive forests (Figure 5.15), although limestone bedrock is rare on the north and mid-coast of British Columbia. Karst topography is a unique landscape, with unusual and distinctive physical features and hydrology. The associated ecosystems have highly productive soils, which support

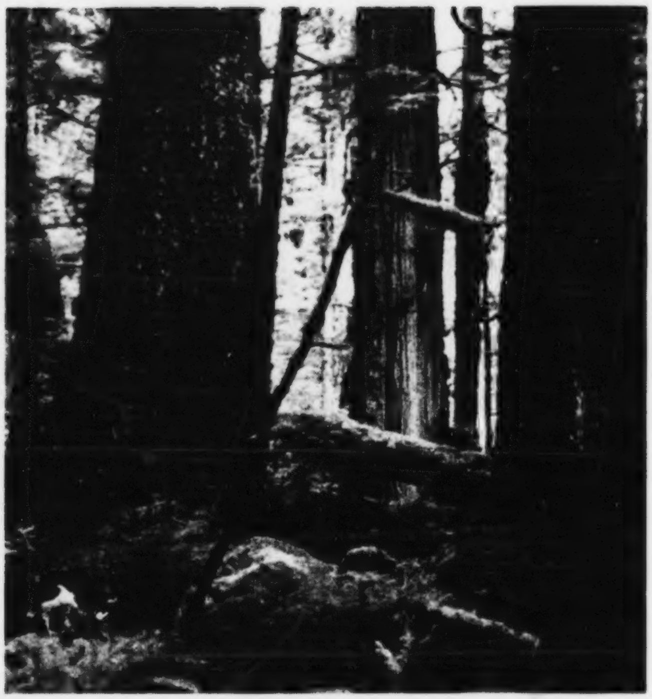


FIGURE 5.15 *Productive Sitka spruce–western redcedar forest on limestone bedrock, Hamner Island.*

populations of specialized invertebrates. Although the combination of productive old-growth forests (CWHvh2/04, /05, and /06) on limestone-karst is very rare in the mainland CWHvh2, harvesting has occurred in stands on limestone because of the relatively high productivity of these stands. Except on karst, productive old forests seldom occur on gentle topography, which usually supports low-productivity ecosystems such as the CWHvh2/01, /11, and /12. Karst ecosystems are incompletely known in the study area. These rare karst ecosystems may occur in the relatively common site series and thus the Conservation Data Centre has not identified them as rare.

We know of several well-developed karst ecosystems in the CWHvh2:

- Chapple–Emily Carr inlets on Princess Royal Island
- northwest Aristazabal Island (and as yet unspecified areas at Kettle Inlet, Switzer Cove, Turtish Harbour–Borrowman Bay, south of Nob Hill; field assessments of these four areas are required)
- east side of Aristazabal Island (area opposite the Ramsbotham Islands has karst, but the limestone deposit was quarried in the past, and recently has been further explored)
- Kumealon Inlet (the karst here has been logged over, but more may exist in the vicinity); some impressive second-growth forests occur on limestone in this area.

Further field assessment and documentation of karst ecosystems are necessary.

Non-forested ecosystems Although the non-forested habitats we describe below should not be directly affected by HyP^3 applications, we include them for completeness, and because these ecosystems are rare, sensitive, and play significant roles in regional landscape diversity.

All seabird islands and marine mammal rookeries and haul-outs are intrinsically unique, and therefore singularly rare (Figure 5.16). Examples include: Lucy Islands; Bonilla Island; North Danger Rocks; Mud Island; Prince Leboo Island; the Moore, Whitmore, and McKenney islands of Ecological Reserve 23; the Dewdney and Glide islands of Ecological Reserve 25; and the Byers, Conroy, Harvey, and Sinnett islands of Ecological Reserve 103. Collectively, these islands are very rare, biologically significant, sensitive to disturbance, and threatened by oil spills, careless recreationists, fishermen, and introduced species; however, these seabird and marine mammal islands will not be directly affected by HyP^3 activities.

All estuaries are unique and are exceptionally biologically productive (Figure 5.17). Ecologically, estuaries are considered "keystone" ecosystems; that is, ecosystems whose influence on the surrounding watershed and landscape is disproportionately large relative to their abundance.

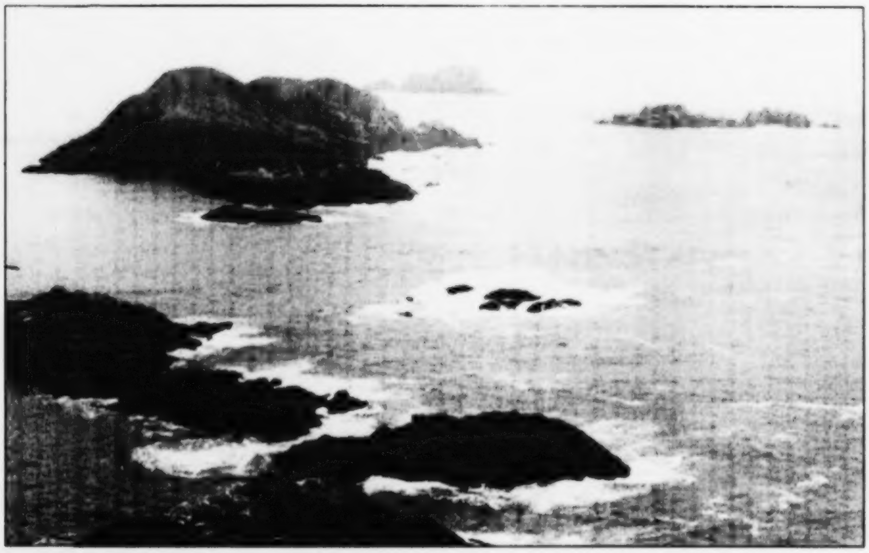


FIGURE 5.16 *Kerouard Islands, south of Kunghit Island, Haida Gwaii/Queen Charlotte Islands.*

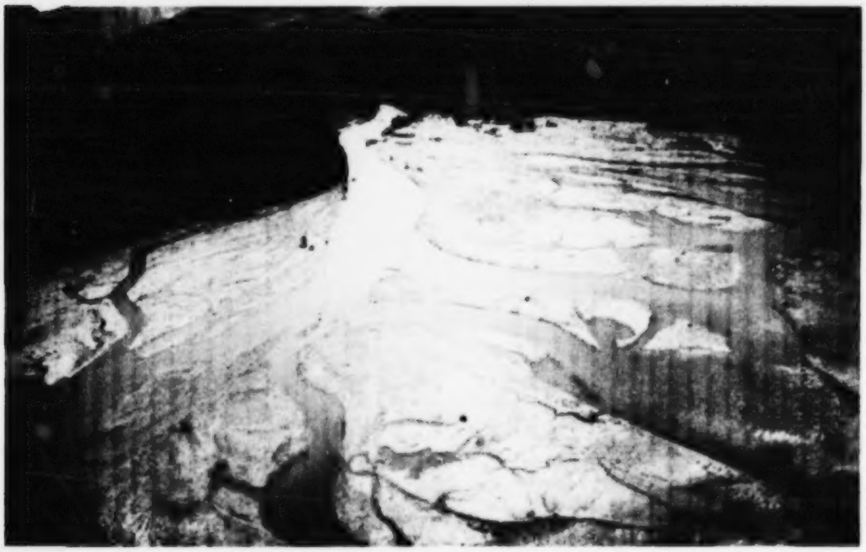


FIGURE 5.17 *Tidal estuary, Kwatna Inlet, east of Burke Channel.*

Estuaries are also very sensitive to marine pollution, excessive harvesting, and susceptible to harvest-related damage from log booming, roads, and camp facilities.

The two largest and most important and complex estuaries in the mainland CWHvh2 are those of the Skeena and Nass rivers. These big estuaries provide habitat for numerous species, such as: juvenile salmon, eulachon, crab, bears, trumpeter swan, brant, great blue heron, western grebe, and many other water birds, as well as rare plants and plant communities on brackish mudflats (MacKenzie and Moran 2004).

Other smaller estuaries in this subzone include the Koeye, Winter Inlet, Kumealon Inlet, Lowe Inlet, Barnard Harbour, and Codville Lagoon; the Koeye is probably the most significant of the smaller estuaries. Significant estuaries also exist in the adjacent CWHvm, including the Stagoo, Kwinamass, Quottoon, Kitikiata-Quall, Klekane, Khutzeymateen, Bay of Plenty, Laredo Inlet, and Kwatna.

High-salinity tidal marshes, mudflats, and eel-grass (*Zostera marina*) beds are also very productive systems, and are especially important as habitat for migratory and wintering water birds and for tidal invertebrates, such as clams and crabs. These ecosystems typically occur as narrow shoreline strips or small pockets. Large expanses of saline tidelands are uncommon and have high conservation values. Notable examples include Big Bay and Kitkatla Inlet (including Billy Bay).

FIGURE 5.18 *Sandy beach on the west side of Calvert Island.*

Sandy beaches are another intrinsically rare type of ecosystem along the rocky, often steep, and predominantly low-energy shoreline of the north coast. Most are very small pocket beaches, as on the west side of Digby Island and on Kitson Island; a few are medium-sized, such as those on Tugwell Island. Large sand beaches occur just south of Cape Caution, and on the west sides of Calvert (Figure 5.18), Campania (McMicking Inlet), and Porcher islands. These beaches are valuable, not only because of their spectacular beauty and Crown land status, but also because the organisms associated with them are sensitive to marine pollution. Tombolos on southwest Princess Royal Island (along Laredo Channel) and Fin and Bonilla islands are rare landforms and sites of special cultural significance.

Although peatlands are common and extensive on the north coast, nutrient-rich, **minerotrophic** fens and marshes are uncommon, and almost never extensive in the CWHvh2 (Figure 5.19). Rich sedge fens and marshes mostly occur as narrow fringes along sluggish streams and the margins of lakes.

5.5.3 Rare plant species or habitats Rare plant species occurring in the CWHvh2/01 forests were investigated as part of the HyP^3 Project. The focus of field investigations was lichens and mosses because of our general lack of knowledge about these plant groups. During harvesting at the Oona River operational trial, lichens and bryophytes were collected from felled trees, and later examined for rare species (Williston 2003b). In addition, the general area of Oona River was assessed for rare species, or species growing on unusual substrates. These collections did not reveal any rare or endangered species of

FIGURE 5.19 *Carex sitchensis* fen near Prudhomme Lake, Prince Rupert.

bryophytes or lichens (Geiser et al. 1994; Goward et al. 1994; Ryan 1996; Goward 1996; Goward 1999); however, the results of this limited survey should not suggest an absence of these species in zonal forests.

Two species of normally terrestrial lichens, *Cladina portentosa* ssp. *pacifica* and *Cladina arbuscula* ssp. *beringiana*, were observed growing as epiphytes on the boles and lower limbs of shore pine in peatlands of north coastal British Columbia (Williston 2001). These lichens have not been previously reported as demonstrating an epiphytic habit; they are likely found as epiphytes in this area owing to their abundance in adjacent terrestrial habitats and the windy, humid maritime climate, which provides suitable dispersal and growing conditions (P. Williston, Gentian Botanical Research; pers. comm., 2004).

Foliicolous lichens and bryophytes (i.e., those that grow on the leaves [including scales and needles] of vascular plants) are relatively rare in temperate North America; they are known only from the rainforests of the northwest part of the continent. Seventeen foliicolous lichens and bryophytes are reported from a single western redcedar growing along the shore of Porcher Island (Williston 2003b). Four species are new to the foliicolous flora of North America, including two lichens, one moss, and one liverwort (Table 5.8). Their presence reflects the distinctively stable, mild, and very humid conditions in coastal rainforests of British Columbia. These forests support a long and favourable season for the establishment and growth of foliicolous lichens and bryophytes.

Though foliicolous species are well known from tropical and subtropical regions, the floristics and ecology of their temperate counterparts have been the subject of only two studies. In 1943, Daubenmire documented eight foliicolous lichens from northwestern Idaho; 30 years later, Vitt et al. (1973) listed 16 lichens and five bryophytes growing on living western redcedar scale leaves from a few localities in coastal Washington and British Columbia. Whether the substrate specificity noted among these organisms is related to nutrient enrichment, pH, or the lack of inhibitory compounds is not known.

The current CDC list of red- and blue-listed vascular plants for the North Coast Forest District does not contain any species that are normally found in CWHvh2/01 forests nor any species that may be regionally rare or at the limits of their distribution, although these species are also not likely to occur on zonal sites (J. Pojar, Canadian Parks and Wilderness Society, Whitehorse, Yukon; pers. comm., 2003).

5.5.4 Animal species of conservation concern The investigation of rare animal species in the CWHvh2/01 was done by consulting local wildlife biologists and using the CDC list of red- and blue-listed animal species for the North Coast Forest District. Three species were identified that may be sensitive to increased harvesting in the CWHvh2/01 forests:

1. the red-listed northern goshawk (*Accipiter gentilis* ssp. *laingi*);
2. the red-listed marbled murrelet (*Brachyramphus marmoratus*); and

TABLE 5.8 *A comparison of foliicolous lichens and bryophytes from Porcher Island and those reported by Vitt et al. (1973) from other coastal localities in British Columbia*

Foliicolous Species	**Porcher Island**	**Vitt et al. (1973)**
Lichens		
Candelariella vitellina (Hoffm.) Müll. Arg.		+
Catillaria bouteillei (Desm.) Zahlbr.		+
Cavernularia hultenii Degel.	+	+
Cetrelia cetrarioides (Duby) Culb. & C. Culb.	+	+
Tuckermannopsis chlorophylla (Willd.) Hale	+	+
Hypogymnia physodes (L.) Nyl.	+	+
Hypogymnia tubulosa (Schaerer) Hav.	+	+
Hypotrachyna sinuosa (Sm.) Hale	+	+
Lecanora pulicaris (Pers.) Ach.		+
Lepraria sp.	+	+
Physcia tenella (Scop.) DC.	+	+
Parmelia sulcata Tayl.	+	+
Placynthiella sp.	+	
Platismatia glauca (L.) Culb. & C. Culb.	+	+
Ramalina farinacea (L.) Ach.	+	+
Rinodina sp.	+	
Usnea sp.	+	+
Xanthoria candelaria (L.) Th. Fr.	+	+
Liverworts		
Frullania franciscana M.A. Howe	+	
Porella cordaeana (Huebener) Moore		+
Mosses		
Orthotrichum consimile Mitt.		+
Orthotrichum lyellii Hook. & Tayl.		+
Orthotrichum pulchellum Brunt.		+
Orthotrichum speciosum Nees		+
Ulota phyllantha Brid.	+	

3. the blue-listed coastal tailed frog (*Ascaphus truei*).

While these species do not depend particularly on CWHvh2/01 forests, they may face an additional threat if harvesting rates increased on the north coast. Research on these species is ongoing in coastal British Columbia. Some genetically unique, insular forms of species may also occur on north coast islands; however, little information exists about this aspect of the area's biodiversity (D. Steventon, B.C. Ministry of Forests, Smithers, B.C.; pers. comm., 2004).

5.6 Predictive Ecosystem Mapping

An ecologically based inventory is required to apply results from ecosystem-based studies such as those conducted for the HyP^3 Project. The **terrestrial ecosystem mapping** (TEM) methods developed for British Columbia (Banner et al. 1996) provide the preferred level of mapping detail and reliability in the application of ecosystem management approaches to landscape units. For very large and remote jurisdictions such as the coastal forest districts, however, detailed field-based TEM is prohibitively expensive and will not be available for the foreseeable future. Alternatives to TEM have been developed and piloted over the past several years in British Columbia and elsewhere. These approaches use existing inventories, and known or expected relationships between ecosystem units (e.g., site series) and inventory attributes, to predict ecological map units (Figure 5.20).

Ecologists and geographic information system (GIS) specialists at the B.C. Ministries of Forests and Sustainable Resource Management in Victoria and Smithers co-operatively developed a Predictive Ecosystem Mapping (PEM) approach called "EcoGen" (Meidinger et al. 2000; Figure 5.21). The result of this initiative is a predictive ecosystem mapping model for the outer coast. To produce predictive ecosystem maps for the North Coast TSA, this model established relationships between ecosystems and forest cover, **Terrain Resource Inventory Mapping** (TRIM), digital elevation models (DEM) and bedrock geology mapping, within the context of refined biogeoclimatic subzone mapping. These maps identify the site series most likely associated with each forest cover polygon and thus help to establish the extent and location of potentially operable poor- and low-site cedar–hemlock forest types.

As part of the HyP^3 Project, an EcoGen pilot was established near Prince Rupert involving 75 000 ha within five 1:20 000 forest cover map sheets. Fieldwork determined the relationships between site series and inventory attributes, such as forest cover features, slope, aspect, water and riparian features, and bedrock type. To produce the final PEM maps, knowledge tables, which were developed for each of the applicable biogeoclimatic units, were used to run the PEM polygon attributes through a knowledge engine (EcoNGen). These first draft maps received a field-based reliability assessment; subsequent refinements to the knowledge tables led to map revisions (Jones 2001). These final EcoGen maps received another reliability assessment that involved polygon checks throughout the area, and comparisons between the EcoGen mapping and the detailed TEM mapping carried out at the Diana Lake and Smith Island intensive study sites (Jones 2001). This reliability assessment indicated that the EcoGen predictive mapping was 67% accurate for the PEM label matching the dominant ecosystem unit on the ground, and 80% accurate when the adjacent ecosystem unit (i.e., adjacent on the edatopic grid) (Figure 2.7) was deemed acceptable.

When the EcoGen initiative started several years ago, the existing available inventories (forest cover, TRIM, bedrock geology) were recognized as significantly limited for use in predicting ecosystems. At that time, a PEM accuracy of 65–70%

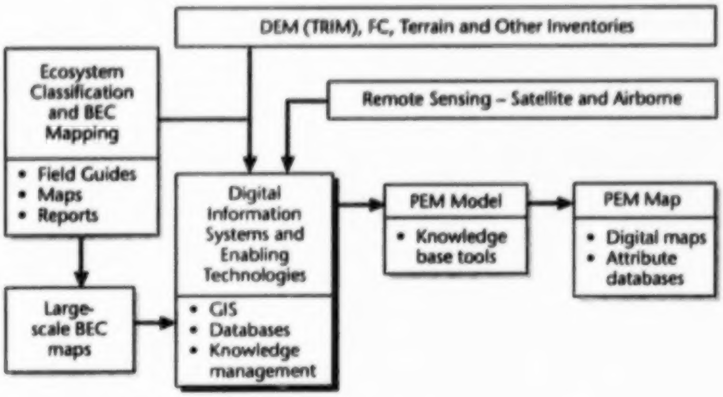

DEM (TRIM), FC, Terrain and Other Inventories
Ecosystem Classification and BEC Mapping
• Field Guides
• Maps
• Reports
Remote Sensing – Satellite and Airborne
Digital Information Systems and Enabling Technologies
• GIS
• Databases
• Knowledge management
PEM Model
• Knowledge base tools
PEM Map
• Digital maps
• Attribute databases
Large-scale BEC maps

FIGURE 5.20 *The predictive ecosystem mapping (PEM) procedure.*

was regarded as a reasonable goal. Recent accuracy assessments of TEM projects around the province range from 65–85%; therefore, the EcoGen results represent an acceptable and more cost-effective (a few cents per hectare vs. a few dollars per hectare) alternative to TEM mapping. Most importantly, EcoGen allows us to get maximum use out of existing inventories before we decide on where additional funds should be directed for more detailed ground-based ecosystem inventories.

Based on the satisfactory results obtained from our pilot EcoGen project on the north coast, we received additional funds to complete EcoGen mapping for the entire North Coast TSA (1.95 million ha), and incorporate further refinements to the knowledge tables and GIS features. This PEM mapping project is now completed (Jones 2003). Further refinements to the biogeoclimatic mapping for the north coast (e.g., better linking of the mapping to the TRIM elevational base) are also complete.

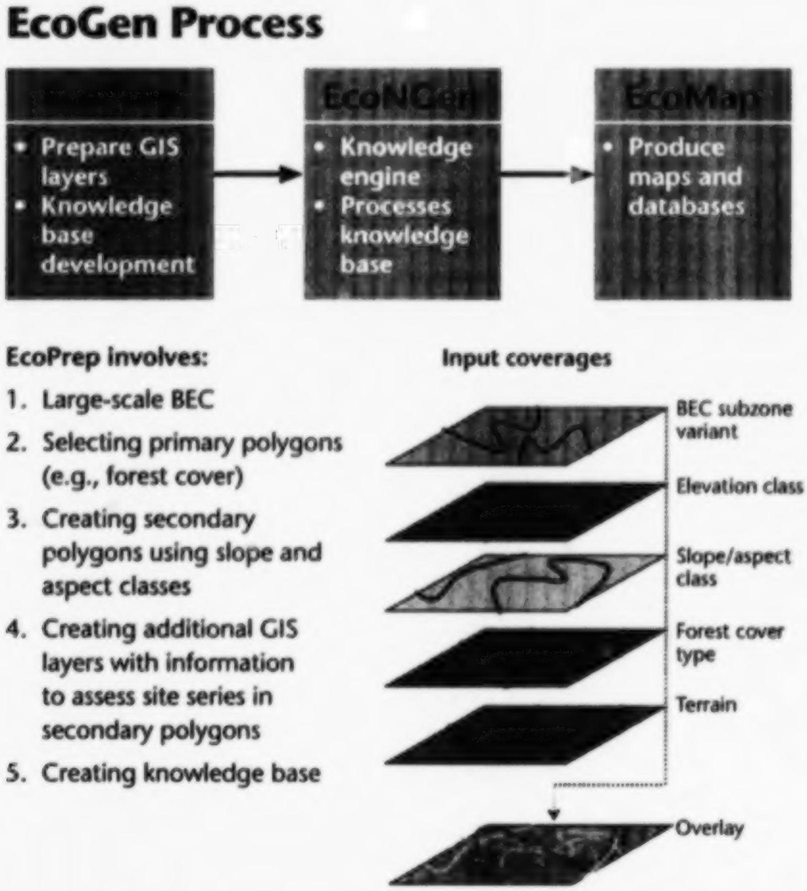

EcoGen Process
EcoNGen
EcoMap
• Prepare GIS layers
• Knowledge base development
• Knowledge engine
• Processes knowledge base
• Produce maps and databases
EcoPrep involves:
1. Large-scale BEC
2. Selecting primary polygons (e.g., forest cover)
3. Creating secondary polygons using slope and aspect classes
4. Creating additional GIS layers with information to assess site series in secondary polygons
5. Creating knowledge base
Input coverages
BEC subzone variant
Elevation class
Slope/aspect class
Forest cover type
Terrain
Overlay

FIGURE 5.21 *The EcoGen predictive ecosystem mapping approach. GIS inventory layers are prepared and overlaid; then the attributes of the resultant polygons are run through a "knowledge table" that is developed for each biogeoclimatic unit. Site series predictions are based on known or expected relationships between polygon attributes and ecosystem characteristics.*

An independent accuracy assessment has now been completed for the North Coast PEM mapping (*Yole and Cushon* 2003) and the results indicate that the CWHvh2 is 75% accurate. As the assessment did not follow the current provincial accuracy protocol (Meidinger 2003), the result is not directly comparable to other map assessments. The result does appear to indicate, however, that the mapping can be used to predict site series composition of forest cover polygons and will thus be a useful tool for determining the location of potentially operable poor- and low-site cedar–hemlock forest types. The PEM maps will also be of use for other strategic planning processes including the implementation of ecosystem-based management on the coast.

A yield analysis project using the five initial EcoGen pilot map sheets is also finished (Olivotto and Meidinger 2001). This analysis used second-growth site productivity (SIBEC) data from the HyP^3 Project (see section 5.3, for a more complete discussion of site productivity issues) to assign site index values to ecosystem polygons. *This ecologically based analysis* was compared with the traditional timber supply analysis, which uses site productivity estimates derived from the (largely old-growth) forest cover inventory. Applying the EcoGen model and second-growth site index data to the yield analysis resulted in significant increases to the mid- to long-term harvest flow in the pilot area. The Land and Resource Management Plan (LRMP) Table for the north coast considered the implications of using these recent ecologically based, second-growth site productivity data for yield analysis. On reviewing the "base case" North Coast Timber Supply Analysis, LRMP table members decided to use the traditional forest inventory productivity estimates, and to incorporate the latest site productivity data in a "sensitivity analysis" (North Coast Government Technical Team 2002).

6 OPERATIONAL RESEARCH TRIALS

6.1 Introduction

The HyP^3 Project established operational research trials at Port Simpson and Oona River. The trial near Port Simpson, north of Prince Rupert, was established in 1990 to examine second-growth productivity in the poor cedar–hemlock forest type. Initially funded by South Moresby Forest Replacement Account (SMFRA) research funds, this study was subsequently taken over by the HyP^3 Project in 1999. The Oona River operational trial is located on Porcher Island, south of Prince Rupert. This is a more expansive trial and was established in 1998 to test some of the management ideas gained from both the Port Simpson trial and the multitude of research studies undertaken on CWHvh2/01 sites around Prince Rupert. These two operational trial sites are described in Chapter 2 (sections 2.6.3 and 2.6.4). Three HyP^3 extension notes also provide information on the Port Simpson and Oona River trials (Appendix 1; Shaw and Banner 2001a and 2001b; LePage et al. 2002).

6.2 Port Simpson

The Port Simpson operational trial is concerned with improving site productivity on imperfectly to poorly drained sites. The trial addresses two specific issues:

1. seedling growth response on artificially mounded and unmounded microsites; and
2. seedling nutrition on five substrate types created by mixing and mounding treatments.

In this study, we hoped to determine the impact of manipulating soil mineral and organic content on seedling nutrition and growth. To do this, we compared tree growth between mounded and unmounded sites. Although mounding has been used for site preparation in other areas of British Columbia (McMinn and Hedin 1990), this is the first trial established in wet north coastal forests. Some baseline hydrological monitoring was also carried out at the Port Simpson operational trial as described in Beaudry et al. (1994) and Beaudry and Sagar (1995) (see Chapter 3, sections 3.2.5 and 3.4.2).

6.2.1 Study area description and research approach The study area is located 30 km northwest of Prince Rupert near the village of Port Simpson (see Figure 2.9), within the CWHvh2. The study area is largely dominated by the Western redcedar – Western hemlock – Salal site series (CWHvh2/01). The major tree species before harvesting included western hemlock, western redcedar, and yellow-cedar, with minor amounts of mountain hemlock, Sitka spruce, and shore pine. Mean height and diameter at breast height (DBH) of main canopy trees were 20 m and 65 cm, respectively. Gross volume per hectare was 500 m^3 and net volume per hectare averaged 280 m^3.

Variability in soil composition and thickness is common on the outer north coast. In general, the soils of the study area consist of deep surface organic horizons (average depth 52 cm). This organic layer is primarily composed of forest humus on drier microsites and sphagnum peat on wetter sites. This layer usually overlays a thin mantle of mineral soil which is often less than 50 cm deep. The soils are mostly classified as Podzolic and the horizons are derived from metamorphic bedrock (schist and gneiss).

The study area was skidder-logged in the late summer and fall of 1990. Following harvest, the treatment area was divided into eight plots (i.e., four plots as mounding treatments and four left as controls), with an average plot size of approximately 0.18 ha. A John Deere 790 DLC excavator equipped with a bucket and thumb attachment created the mounds (Figure 6.1a). The objective was

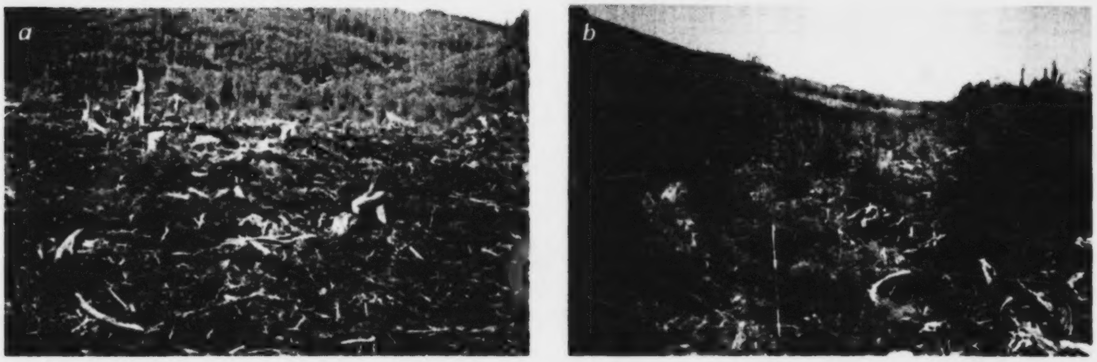


FIGURE 6.1 *Port Simpson mounding trials: (a) after completion of mounding in 1990; and (b) 6 years after planting.*

to build the mounds by overturning one scoop of soil and then mixing the mineral horizons with the surface organic horizons. Mounds averaged 0.5 m in height and 1.5 m in diameter. Mound density varied from 250 to 670 per hectare. The mounding treatment resulted in five substrate types (Table 6.1). The two unmounded substrates are controls representing post-harvest conditions typical of poorer forested sites of the north coast. In the mounded treatments, soil variability resulted in three substrate types differing by degree of mixing and mineral and organic composition.

TABLE 6.1 *Substrate descriptions at Port Simpson mounding trial*

Substrate	Composition
A	Undisturbed LFH[a] and LFH with surface disturbance (unmounded)
B	Undisturbed peat and peat with surface disturbance (unmounded)
C	Mineral mound with low organic incorporation
D	Mineral mound with moderate to high organic incorporation, usually humus
E	Organic mound, dominantly O (peat) material

a LFH = forest floor horizons.

In the spring of 1991, mounded and unmounded plots were planted with equal proportions of western hemlock, western redcedar, and shore pine. Height and caliper of planted trees were measured in 1991, 1992, 1994, and 1996. In 1997, whole trees were collected from both the mounded and unmounded sites (Figure 6.1b). At that time, 63 trees were manually excavated to compare root development between the mounded and unmounded plots. In addition, 28 soil samples were collected for chemical analysis, and foliar samples of new growth were taken from the upper crown of 63 planted trees. Soil and foliar samples were collected from each of the five substrate types.

6.2.2 Port Simpson results Five years after planting, shore pine and hemlock showed significant treatment effects ($p < 0.05$). Both species exhibited a 30% increase in mean height growth and a 66–68% increase in mean caliper growth on the mounded sites (Figure 6.2). Western redcedar, however, did not exhibit a significant difference between treatments ($p > 0.05$). Preliminary results show western redcedar did marginally better on mounded sites in average height growth, but differences in caliper growth were negligible between treated and untreated areas.

Although no difference in root to shoot ratios was evident between treatments, the mean weight of root and shoot biomass increased on the mounds for all species. Western hemlock and shore pine both exhibited significant increases in root and shoot biomass between treatments (Figure 6.3). Both mean above- and below-ground biomass doubled for western hemlock and tripled for shore pine on mounded sites. Western redcedar also showed increases in root and shoot biomass between treatments, but the differences were not significant ($p > 0.05$).

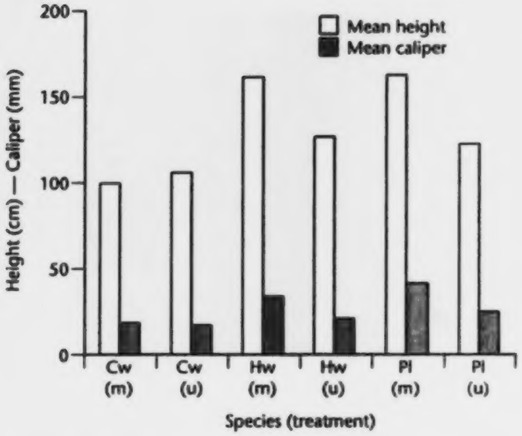


FIGURE 6.2 *Mean height and mean caliper of western redcedar (Cw), western hemlock (Hw), and shore pine (Pl) 5 years after planting on mounded (m) and unmounded (u) plots at the Port Simpson study site.*

Rooting depth on mounded sites also showed a significant difference for all species (Figure 6.4). Mean rooting depth was 75–100% greater for all three species growing on mounded sites compared with unmounded sites (Figure 6.5). The mean length of the longest lateral root was also greater on the mounds, especially for western hemlock (28% increase) and shore pine (37% increase). In many cases, lateral roots extended well beyond the limits of the mounds.

In general, western redcedar performed poorly compared with shore pine and western hemlock, and showed no significant difference in height and caliper between treatments ($p > 0.05$). Overall mortality throughout the study area was

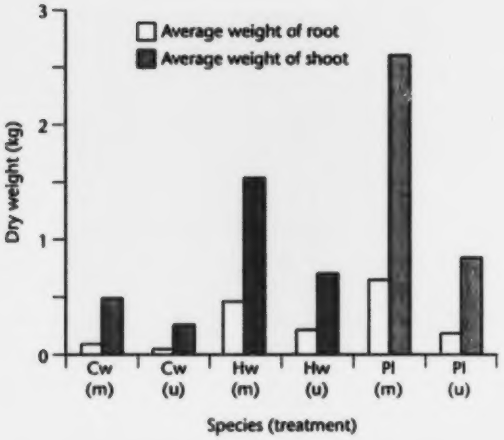


FIGURE 6.3 *Root and shoot biomass of western redcedar (Cw), western hemlock (Hw), and shore pine (Pl) 6 years after planting on mounded (m) and unmounded (u) plots at the Port Simpson study site.*

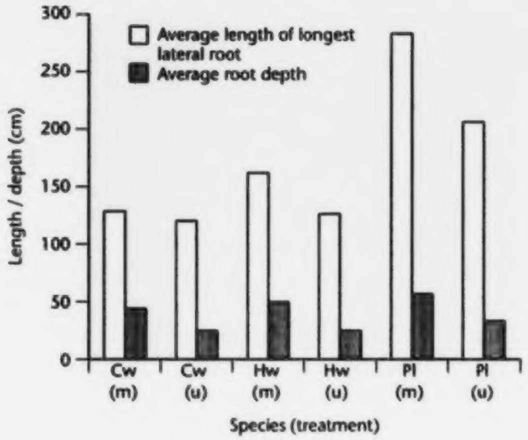


FIGURE 6.4 *Rooting characteristics of western redcedar (Cw), western hemlock (Hw), and shore pine (Pl) 6 years after planting on mounded (m) and unmounded (u) plots at the Port Simpson study site.*

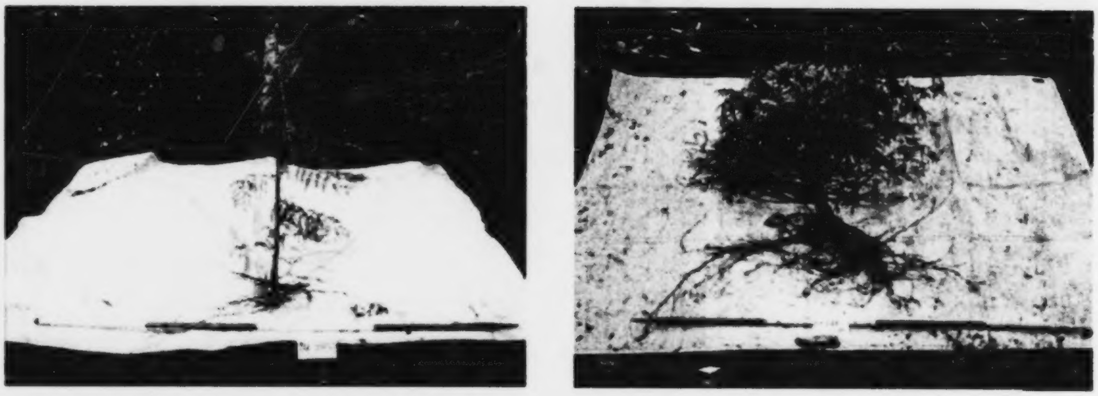


FIGURE 6.5 *Root development of western redcedar growing on unmounded (left) and mounded (right) plots 6 years after planting at the Port Simpson study site.*

also greatest for redcedar (68%) compared with western hemlock (26%) and shore pine (14%). The increased mortality and poorer growth response was largely attributed to the poor condition of the cedar stock (i.e., low root to shoot ratios) and heavy deer browsing after planting (seedlings were not initially protected). Although these factors have complicated the interpretation of treatment effects on western redcedar, the biomass and root growth data showed some positive trends related to treatment.

Initial trends suggest that mounding treatments can have a positive effect on shoot growth, above- and below-ground biomass, and root development for seedlings planted on these imperfectly to poorly drained sites (Figure 6.5). The mounding treatment resulted in soil mixing that revealed some other important trends in seedling growth and nutrition. The variable thickness of mineral and organic horizons, and the nature of the soils throughout the study area, created considerable variation in mound characteristics. We observed trends in seedling response that reflected this variation in substrate type, with the best growth occurring on mixed mineral-organic mounds and the poorest growth response on pure organic (especially peat, rather than forest humus) mounds.

Results of the foliar nutrient analysis support these findings (Figures 6.6 and 6.7). In general, shore pine needles from seedlings growing on mineral mounds had the greatest needle mass and content of all macro- and micronutrients. The mineral–forest floor mix of substrate D yielded a

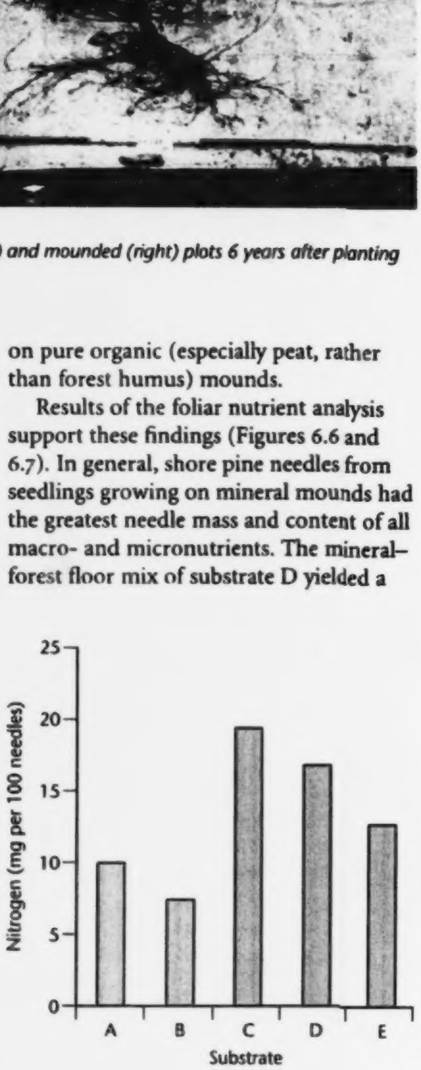


FIGURE 6.6 *Nitrogen content of pine needles from trees growing on five substrate types (see Table 6.1) at the Port Simpson study site.*

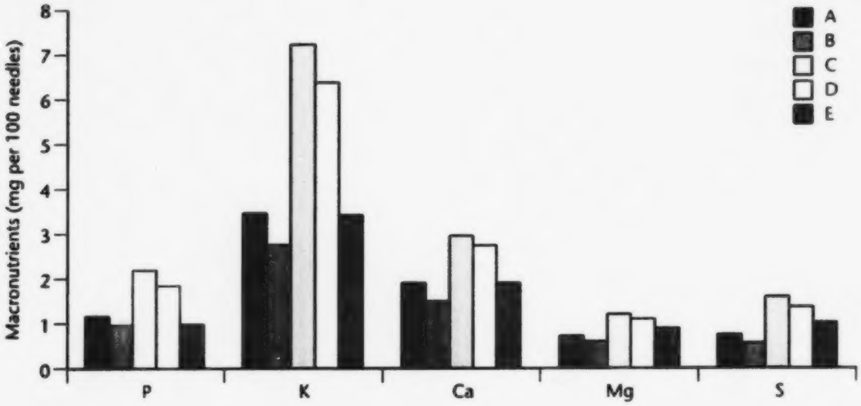


FIGURE 6.7 *Macronutrient content of pine needles from trees growing on five substrate types (see Table 6.1) at the Port Simpson study site.*

slightly lower needle mass and content of macro- and micronutrients, followed by mounded peat (substrate E). The unmounded peat of substrate B yielded the lowest foliar mass and nutrient content of all substrates tested.

Because of the dramatic differences in foliar mass among the various substrate types, foliar nutrient concentrations (expressed as a percentage of foliar weight) did not reflect the differences in productivity. In situations like this (i.e., where a series of treatments gives rise to significant differences in biomass production), expressing the foliar nutrient data in terms of content (milligrams per 100 needles) instead of concentration avoids the "dilution" complications brought about by the biomass differences (Ballard and Carter 1986). Interpretations of foliar nutrient data are not straightforward in these situations, but it is reasonable to conclude from the Port Simpson trial that initial productivity and nutrient uptake has been improved by the mounding treatments. Although this may be partially attributed to improvements to microsite drainage, the mixing of mineral and organic horizons, similar to the natural turbation resulting from windthrow and landslide events, is likely the more critical element in improving soil nutrient regimes (Bormann et al. 1995).

We recognize that the Port Simpson trial is only a preliminary investigation. Future studies should focus on the differences in tree species response to mixing and mounding treatments, acceptable levels of site disturbance, impacts on paludification (see sections 4.3 and 4.4), and optimal treatment methodologies. Although not included in this trial, yellow-cedar is an important species on these sites and should be included in future research. The trends we observed at Port Simpson helped direct the design of the Oona River operational trial.

6.3 Oona River

The Oona River trial was established with the overall objective of examining the ecological and operational feasibility of harvesting and regenerating lower-productivity forests. This trial set out to:

- Assess the feasibility of harvesting lower-productivity western redcedar–western hemlock stands.
- Test the efficacy of fertilization and mechanical site preparation treatments for promoting the establishment and growth of natural and planted conifers.

- Compare the factors affecting establishment and growth of western redcedar following harvesting.
- Assess and compare the growth performance of planted and natural western redcedar.
- Assess the nutritional status of seedlings established on a variety of microsites with and without the application of fertilizer.
- Document the growth history and productivity in lower-productivity, old-growth western redcedar–western hemlock stands and compare this with second-growth productivity on similar sites.
- Assess the quality of timber harvested from these lower-productivity stands.
- Document end-product recovery and utilization rates.

6.3.1 Study area description and research approach The Oona River trial is located near the community of Oona River on Porcher Island, 40 km south of Prince Rupert (see Figure 2.9). The operational area consists of two adjacent blocks that cover a total of 17.6 ha (10.2 and 7.4 ha, respectively). The trial is also situated within the CWHvh2 subzone, and includes three site series: Western redcedar – Western hemlock – Salal (CWHvh2/01) covers approximately 84% of the harvested area; Western redcedar – Yellow-cedar – Goldthread (CWHvh2/11) covers 10%; and Western hemlock – Sitka spruce – Lanky moss (CWHvh2/04) covers 6%. Both blocks occur on gentle slopes (5–25%) with a southerly aspect. Soils are imperfectly to poorly drained and consist primarily of organic LFH, or peat veneers over saprolitic veneers (decomposed schistose bedrock). Soil depth varies from 20 cm to over 100 cm. Stands in the area are dominated by western redcedar, which accounts for about 50% of the volume, and western hemlock, with lesser amounts of yellow-cedar, Sitka spruce, and shore pine. Based on a pre-harvest timber cruise, gross and merchantable volumes within the CWHvh2/01 site series were 333 m^3/ha and 235 m^3/ha, respectively.

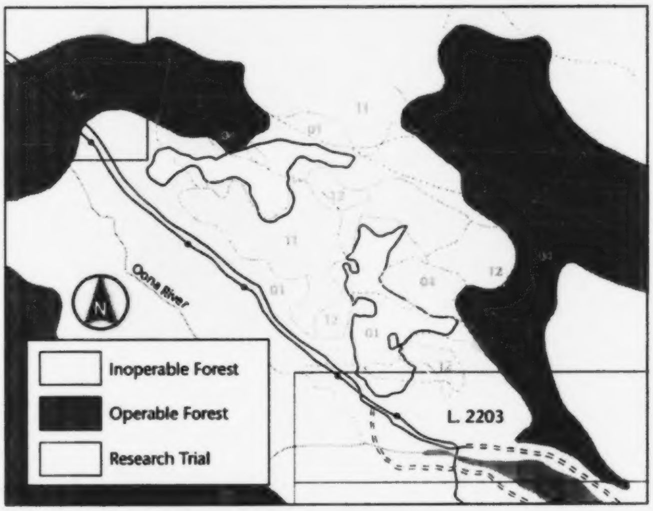


FIGURE 6.8 *Ecosystem map of Oona River study site showing preliminary block boundaries that primarily encompass the Western redcedar – Western hemlock – Salal (CWHvh2/01) site series.*

In 1998, timber cruising and ecosystem sampling were carried out within a 50-ha candidate area to identify sites dominated by the CWHvh2/01 site series. Using the ecosystem sampling data, together with field notes and air photo interpretation, an ecosystem map was produced for the study area. Preliminary block boundaries were laid out to include mainly the CWHvh2/01 site series (Figure 6.8). Additional cruise plots were established within both blocks to obtain more detailed information on species distribution, stand structure, and wood quality. Detailed soil depth and ecosystem mapping was also conducted on a 50-m grid within each block. A 1:3000 ecosystem–soil depth map was produced for both blocks to refine the original block boundaries, identify wetter leave patches (mostly site series CWHvh2/13 [Western redcedar – Skunk cabbage] and CWHvh2/11), and plan harvesting and silvicultural treatments.

Block harvesting began in June 2000. Following a diameter limit approach, all western redcedar and yellow-cedar between 17.5 cm and 150 cm DBH were felled. Western redcedar and yellow-cedar less than 17.5 cm DBH were retained for crop trees in the next rotation, and those greater than 150 cm DBH were retained as seed and wildlife trees. The majority of hemlock and shore pine greater than 2 m in height were also felled; since neither species was considered as a crop tree for the next rotation, leave-tree specifications were not required. Hand-felling was completed over several weeks. The main skid roads were constructed with an excavator using non-merchantable wood (rotten logs, snags, and undersized stems) as corduroy material. One main skid road was constructed through the centre of each block, with short spurs constructed to access block extremities (Figure 6.9). Logs were "hoe-chucked" to the main skid roads using a CAT 320L, wide-tracked (32-inch) excavator (Figure 6.10) and moved to the haul road by a low-ground-pressure (< 6 PSI) FMC tracked skidder equipped with chokers (Figure 6.11).

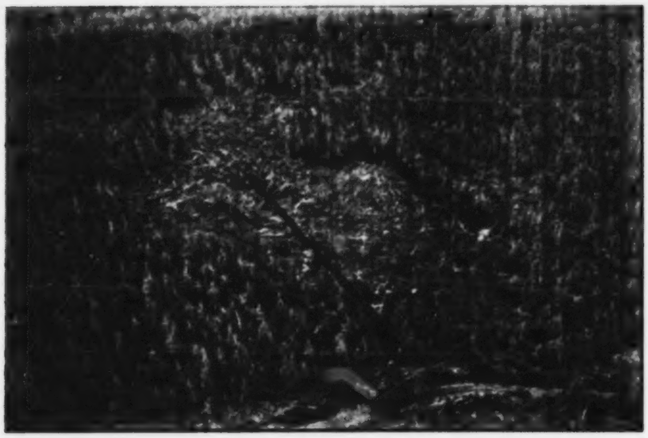


FIGURE 6.9 *Block 1 at the Oona River study site showing the main corduroy skid trail.*

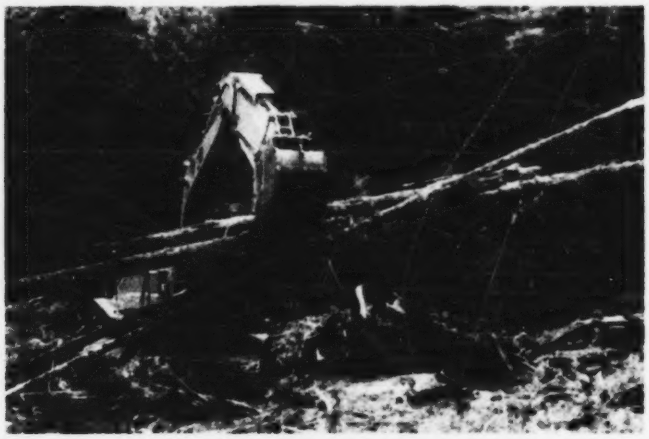


FIGURE 6.10 *Excavator "hoe-chucking" logs to main skid trail at the Oona River study site.*

Following harvest, twelve 0.1 ha treatment plots were laid out across the two blocks. Uniformity in slope, soil moisture, and soil depth were major criteria for plot selection. Areas dominated by peaty soils (mainly site series CWHvh2/11) were not included in the plots. The site treatments selected for the operational trial were based on existing knowledge of ecosystem processes and the results of the research trial established on similar sites near Port Simpson (Shaw and Banner 2001a and 2001b). The Port Simpson trial indicated that planted seedlings generally performed better on mounds which consisted of a mixture of organic and mineral soil horizons. In addition, experience on northern Vancouver Island (Prescott and Weetman 1994) has shown good tree growth response to fertilization with nitrogen (N) and phosphorus (P). We, however, hypothesize that the addition of P alone will enhance N availability by stimulating the nitrogen cycle (Cole and Heil 1981; White and Reddy 2000) (See Chapter 4, section 4.5.3).

The lower-productivity sites contain a huge amount of organic material (e.g., dead and down trees, humus layers, moss, and vegetation). Disturbance of the surface organic soil layers and the removal and/or mixing of excess organic material can warm the soil, increase soil aeration, and subsequently improve nutrient availability. Surface scarification could also create better seedbeds for natural regeneration of western redcedar. Based on the above rationale, the following three site treatments were randomly assigned to the plots (4 replications of each):

1. Light surface scarification, and raking and piling of slash (Figure 6.12).
2. Light scarification and raking (as above) combined with applications of phosphorus fertilizer at the rate of 75 kg/ha.
3. Spot-raking followed by mixing the organic and mineral soil horizons to form low mounds (Figure 6.13).

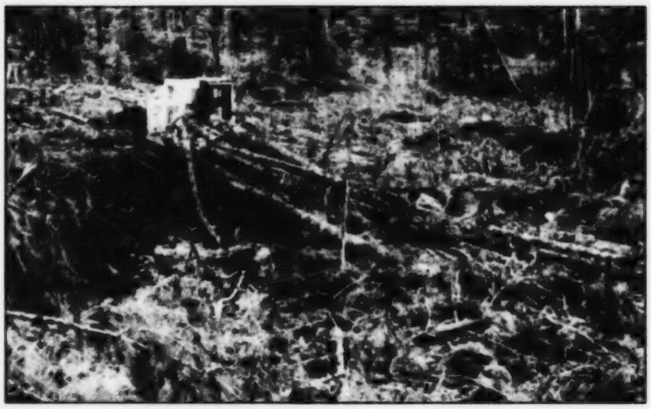


FIGURE 6.11 *FMC tracked skidder moving logs to the landing at the Oona River study site.*

All mechanical treatments were carried out using a wide-tracked excavator equipped with either a five-fingered brush rake or a bucket. Disturbance in the remaining area of the blocks (excluding treatment plots and trails) resulted only from logging activities (felling, forwarding, and excavator travel).

Both blocks were planted with a mixture of western redcedar (61%) and yellow-cedar (39%) in April 2002. To determine optimal regeneration methods for these lower-productivity sites, we will examine the factors that affect the establishment and growth of both natural and planted western redcedar seedlings. These factors include substrate composition, degree of soil disturbance, proximity to seed trees and stand edges, vegetation competition, and deer browsing. After 5 years, we will also assess the nutritional status of planted and naturally regenerated trees, with and without the application of fertilizer. Within the blocks, we will monitor the natural regeneration of all coniferous species (western redcedar, yellow-cedar, western hemlock, shore pine, Sitka spruce, and amabilis fir), and compare the survival rates and growth patterns of natural western redcedar and yellow-cedar with the planted stock.

FIGURE 6.12 *Excavator raking and piling slash in block 1 at the Oona River study site.*

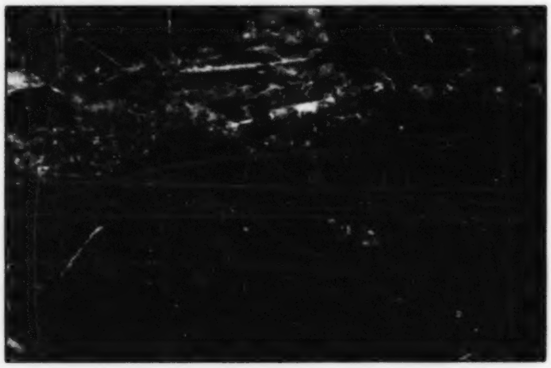


FIGURE 6.13 *Mixed mineral and organic mound on a CWHvh2/01 site at the Oona River study site.*

Heavy browsing of western redcedar seedlings by the large deer population on Porcher Island continues to impede the successful artificial regeneration on operational sites; therefore, all seedlings planted within the treatment plots were protected using 122-cm VEXAR® rigid tubes, double-anchored with cedar and bamboo stakes. These protectors were also used throughout the remaining area within the blocks. Three other seedling protector designs (Growcone® tubes, Sinocast® cones, and Free-Grow® shelters) were also installed on a limited number of seedlings. (Figure 6.14). We will monitor these protectors to assess their susceptibility to wind and snow damage, and their effectiveness in promoting seedling survival and growth.

To determine how second-growth site productivity compares with that of the old-growth forests on these low-productivity cedar–hemlock sites, we needed some background information on the growth history of the existing old-growth forest. Before harvesting, we identified 37 dominant and co-dominant sample trees for stem analysis (Figure 6.15). The sample trees were used to gather growth history and old-growth site productivity information to refine existing site index and rotation length estimates for these lower-productivity sites. We will compare the growth history data from the operational trial with data gathered from the Smith Island and Diana Lake old-growth study sites and with ongoing growth studies in second-growth stands.

One of the overall goals of the HyP³ Project was to assess the feasibility of conducting commercial forestry operations on these lower-productivity sites. Project researchers, therefore, recognized that, in addition to ecological concerns, questions would arise about the quality and value of the available timber. Two areas of concern were identified:

1. the utilization levels (volume and grade) expected from the timber found on these sites; and
2. the achievable levels of end-product recovery.

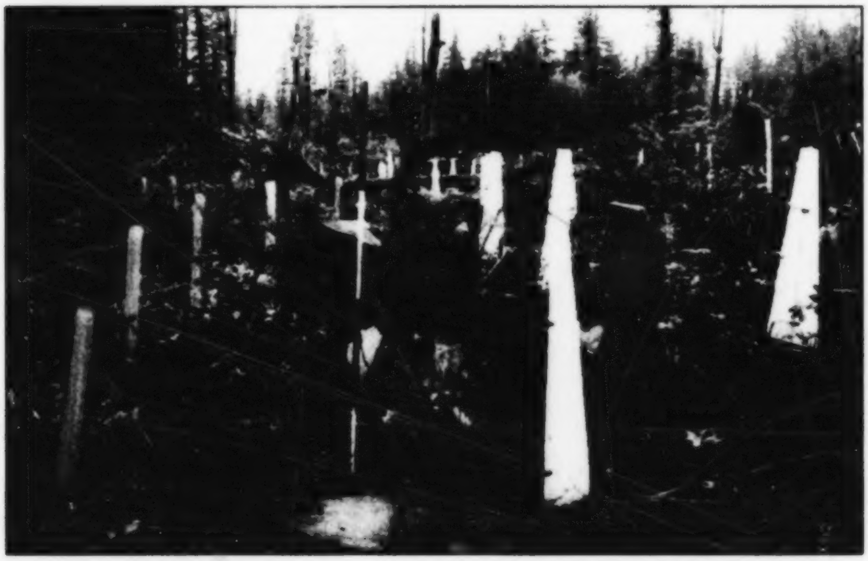


FIGURE 6.14 *Seedling protectors tested at the Oona River study site: Free-Grow® (left), Sinocast® (front right), and Growcone® (back right).*

FIGURE 6.15 *Western redcedar sample tree marked for stem-analysis cutting.*

To address the first point, a detailed field assessment of log quality was completed. This assessment compared standard timber cruise grades with grades obtained from "call-grading." Log grades from a standard cruise are assigned by a computer program that tallies pathological indicators and compares them with a standard database for timber growing on similar sites. With call-grading, each tree in a cruise plot is physically checked for visible pathological and quality indicators and sounded to determine the presence or absence of rot. A log grade is then assigned in the field by the cruiser. Because very limited harvesting of CWHvh2/01 sites has taken place, an assignment of standard cruise-based log grades is highly suspect. To address concerns surrounding end-product recovery, the volume of dimensional lumber produced at the Group Mills sawmill at Oona River was compared with the scaled volume of logs entering the mill. The milling trial used a random selection of log grades and included logs from the #2, #3, and #4 sawlog and #5 utility grades. For a complete description of log grades, refer to B.C. Ministry of Forests (1994).

6.3.2 Oona River results Pre-harvest ecosystem mapping proved an effective tool in helping to delineate block boundaries. The irregularly shaped, relatively small blocks that resulted from following the boundaries of the CWHvh2/01 site series will not only help to promote the natural regeneration of western redcedar with seeds coming from adjacent stands, but will also blend well into the blanket bog–upland forest landscape pattern (Figure 6.16).

Although the Oona River trial consisted mainly of the CWHvh2/01 site series, soil conditions varied considerably throughout the blocks—a situation that had operational implications. For example, soil puddling and surface water ponding occurred in some flat or gently sloping areas, especially where soils were shallow. Excavator mixing and mounding treatments in these areas were more likely to degrade the site and produce negative hydrological impacts than to improve microsites for seedling establishment and growth. Therefore, in the wettest portions of the block, the passes with the excavator were minimized and naturally elevated microsites used for planting seedlings. Throughout the bulk of the blocks where slopes were greater than 15–20%, the mixing and mounding treatments were more successful in providing beneficial soil disturbance and improving microsite drainage.

Lower-productivity coastal forests have a high degree of structural diversity with many veteran trees and snags. The felling of these non-merchantable trees during harvesting operations can lead to very large accumulations of woody slash on sites that already have excessively deep surface organic horizons. To reduce the amount of organic material (decaying

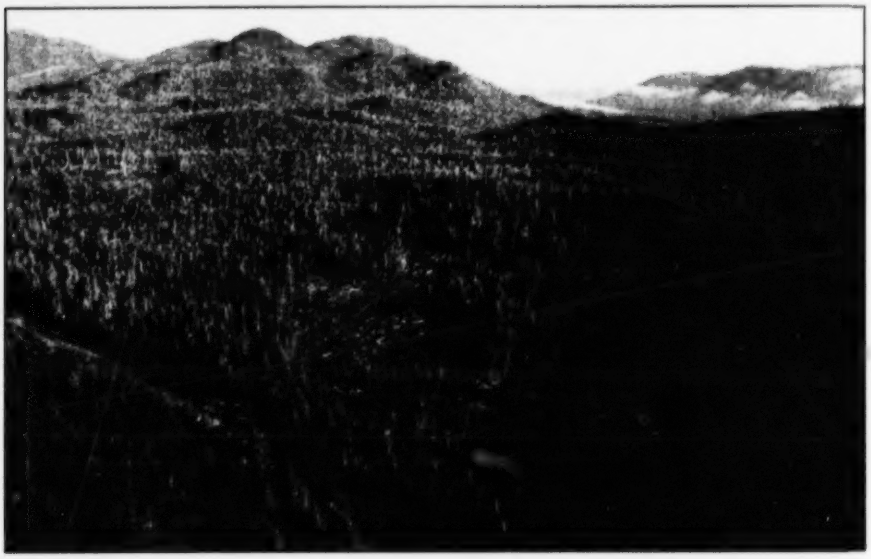


FIGURE 6.16 *Aerial view of block 1 at Oona River showing the irregular ecosystem-based boundaries and the individual and patch leave trees.*

wood) added to the forest floor, these trees should be left standing wherever possible (Figure 6.16). Trees left as seed trees and wildlife trees can contribute to habitat diversity goals. Although the diameter limit approach used in this trial proved effective in meeting objectives for both slash management and seed and wildlife trees, a liberal interpretation of the existing wildlife danger tree assessment guidelines was required. Developing harvesting guidelines for these lower-productivity sites will pose significant challenges as the desire to leave as many veteran green trees and snags as possible must be tempered with the need for safety. Chapter 7 provides more details on harvesting and site treatment options and guidelines for these sites.

In the fall of 2003, survival and height growth assessments of the planted western redcedar seedlings took place in each of the treatment plots. Overall survival was excellent and exceeded 96% in all treatment plots (Table 6.2). This is especially encouraging because of the typically poor

TABLE 6.2 *Average percent survival and height[a] (cm) of planted western redcedar seedlings at Oona River*

Plot no.	Treatment	Survival (%)	Average height (cm)
C1	Control	98	51.8
C2	Control	98	53.3
C3	Control	100	46.9
C4	Control	100	49.4
Average		**99.0**	**50.4**
4	Mound	100	64.1
5	Mound	98	55.5
10	Mound	100	56.7
11	Mound	100	59.2
Average		**99.5**	**58.9**
3	Rake and Fertilize	100	53.8
6	Rake and Fertilize	100	52.7
7	Rake and Fertilize	100	50.6
13	Rake and Fertilize	100	53.0
Average		**100**	**52.5**
1	Rake	96	55.2
2	Rake	98	51.6
8	Rake	100	50.9
9	Rake	100	55.7
Average		**98.5**	**53.4**

[a] Survival and height growth were measured after two growing seasons (3-year-old trees)

survival rate of unprotected seedlings planted in nearby operational blocks and the associated uncertainties in establishing a viable second-growth crop. Although it is too soon to examine the results for significant differences in height growth, some early trends were observed. The untreated controls showed the least height growth and the mounded plots showed the best growth (Table 6.2). Both the raked and the raked and fertilized plots had similar growth, but averaged only marginally more than the control plots (Table 6.2).

Stem analysis of naturally established western redcedar growing in old-growth forests has shown that initial height growth is very slow on these CWHvh2/01 sites (see Table 5.1). Across all treatments, the average initial height growth rate of the planted seedlings in clearcuts is approximately seven times that of the natural seedlings in old-growth forests (17.9 cm/yr vs. 2.6 cm/yr).

Current site index estimates in the forest cover database are derived primarily from measurements of old-growth stands. Most of the CWHvh2/01 sites are classified as "low" and have an assigned site index of 10 m or less. Detailed stem analysis of old-growth western redcedar growing on CWHvh2/01 sites at Oona River confirms that conifer growth in the existing forests is indeed poor and that the actual site index averages just 4 m for trees that regenerated within the undisturbed old-growth forest. Stem analysis also revealed that, on average, these trees take 50 years to reach breast height under the old-growth canopy (see Table 5.1). Preliminary data collected from second-growth stands on the same site series at other locations suggest, however, that the second-growth site index for western redcedar is actually closer to 18 m and the average time to reach breast height is just 7 years (see Table 5.1). Mounding or other site preparation treatments may reduce this time even further. Although a site index of 18 m is still relatively low for coastal forests, it is significantly higher than indicated by the current forest cover inventory (8–10 m). This information is encouraging and reinforces the belief that some level of disturbance to these sites will provide a beneficial boost to tree growth and forest productivity. Indeed, some sites currently classified as "inoperable" because of poor growth rates may well prove manageable in the near future.

Table 6.3 presents a detailed comparison of log quality, as determined by cruise and call-grade methods, for the trees harvested from the Oona River operational trial blocks. The results indicate that the current cruise compilation programs,

TABLE 6.3 *Cruised and call-graded merchantable timber volumes (m³/ha), by log grade and species, from the Oona River operational research trial*

		Western redcedar		**Yellow-cedar**		**Western hemlock**		**Shore pine**		**Sitka spruce**		**Total**	
Log type[a]	**Grade**[a]	**Cruise**	**Call grade**	**Cruise**	**Call grade**	**Cruise**	**Call grade**	**Cruise**	**Call grade**	**Cruise**	**Call grade**	**Cruise**	**Call grade**
#2 Lumber	F		0.6										0.6
#2 Sawlog	H	12.3	16.5							4.9	3.9	17.2	20.4
#3 Sawlog	I	2.5	9.5			1.7				2.5	3.7	6.6	13.2
#4 Sawlog	J	39.4	40.8	16.1	5.8	22.9	8.5	4.9	1.6	14.5	6.8	97.8	63.5
#2 Shingle	L		4.7										4.7
#5 Utility	U	53.0	16.3	4.0	13.9	24.7	12.0		0.8	4.4	4.8	86.0	47.8
#6 Utility	X	2.5	9.6	1.6	0.5	6.3	22.0		1.8		3.5	10.3	37.3
#7 Chipper	Y	13.6	25.3	0.7	2.2	1.7	14.9		0.7	1.1	4.5	17.0	47.5
Total		**123.2**	**123.2**	**22.4**	**22.4**	**57.3**	**57.3**	**4.9**	**4.9**	**27.3**	**27.3**	**235.1**	**235.1**

[a] For log type and grade definitions, see: http://www.for.gov.bc.ca/tasb/legsregs/forest/faregs/scalreg/sr-1.htm#part 1

developed for more productive coastal sites, do not provide an adequate portrayal of the log-quality profile obtained from harvesting lower-productivity western redcedar–hemlock stands on the north coast. For western redcedar, the biggest difference between the cruised and call-graded volumes was the significant decrease in #5 utility logs. Forty-nine percent of this volume was moved into higher-quality and more valuable logs (L grade or better). For western redcedar, the field-based method of call-grading resulted in a 24% increase in the volume of sawlogs. For the other harvested species, significant decreases resulted in the volume of sawlogs and a corresponding increase in the volume of lower-grade utility and chipper logs, again indicating the inadequacies of the current log-quality profile for these sites (Table 6.3).

The western redcedar growing on the imperfectly drained zonal sites on the outer north coast are typically much shorter and have a larger butt flare than those growing on better-drained, more productive sites. In addition, the tree tops are often dead (spike-topped). This type of log profile presents a significant challenge for any lumber processing facility trying to achieve acceptable utilization levels. When sawing these western redcedar logs to produce dimensional lumber, the high degree of taper and numerous large branch knots in the top of the tree, combined with the large butt flare, can result in significant waste. Initial results of the Oona River milling data show that of a typical tree producing three 5-m logs, the total accumulated waste averaged 46% (27% from the butt log, 14% from the top log, and 5% from the centre log). Although the Group Mills facility is a basic operation using a twin-bladed circular saw with a 0.25-inch kerf for primary breakdown, this amount of waste is still within the normal range for milling western redcedar. More modern facilities typically experience total accumulated waste in the 45–55% range, depending on the log grade milled (P. Edwards, International Forest Products, pers. comm., 2004; M. Wilson, Delta Cedar Products Ltd., pers. comm., 2004). An increase in end-product recovery in our study would have been possible if:

- shorter pieces of lumber (< 6 ft.) from the butt log were utilized,
- less one-inch material was cut, and
- the primary headrig was a more efficient, narrow-kerf bandsaw.

If logs were processed in a facility with true taper-sawing capabilities, even more volume recovery would be possible. Despite the problems associated with milling the logs, the quality of the western redcedar dimensional lumber and siding produced from these lower-productivity stands is very high (Figure 6.17).

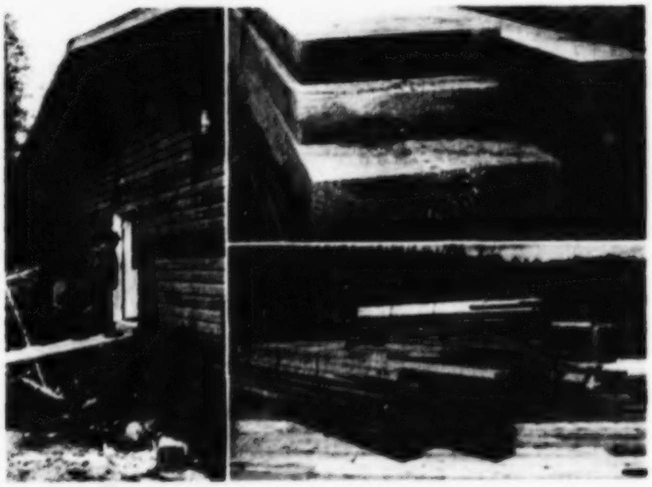


FIGURE 6.17 *Some redcedar siding and dimensional lumber produced at the Group Mills operation at Oona River. Sawlogs were harvested from the nearby operational trial.*

7.1 Identification of Potentially Operable Sites

Marginally operable, low-productivity sites in the CWHvh2 belong primarily to the Western redcedar – Western hemlock – Salal site series (CWHvh2 /01; Banner et al. 1993). Although there is a range of productivity and species composition within the site series, the vast majority of these sites are currently outside the operable land base. At the upper end of the productivity spectrum for this site series, soil and vegetation conditions become transitional to the Western hemlock – Sitka spruce – Lanky moss site series (CWHvh2/04), which is currently included in the operable land base. At the lower extremes of productivity for the CWHvh2/01 site series, conditions are transitional to the Western redcedar – Yellow-cedar – Goldthread site series (CWHvh2/11), in which standing wood volumes are well below current and projected operability limits (typically less than 150 m^3/ha).

We have summarized data from over 400 ecological plots collected by the B.C. Ministry of Forests between 1978 and the early 1990s, as well as additional data collected by HyP^3 researchers between 1998 and 2002. These data have been used to develop better descriptions of these hypermaritime ecosystems, especially for the lower-productivity forest types of interest in this study. By combining this information with HyP^3 Project results from our intensive study sites and operational trials, we have defined a set of criteria to identify those CWHvh2/01 sites with the greatest potential for sustainable forest management (Table 7.1). These criteria include: depth and nature of mineral and organic soil horizons, bedrock geology, overstorey and understorey composition, and stand volume. Other information, such as location and accessibility, should be used in combination with these site factors to determine overall operability.

Ultimately, these site identification criteria, and additional information on bedrock identification and silvicultural strategies, will be summarized in a supplement to *A Field Guide to Site Identification and Interpretation for the Prince Rupert Forest Region* (Banner et al. 1993). This information will help to assess lower-productivity cedar-dominated sites under consideration for harvesting. These criteria are not absolute, however, and the final decision on operability must weigh positive indicators against negative ones. We will further refine the operability criteria with monitoring information from the operational trials as we gain more experience in these forest types.

7.2 Silvicultural Systems

A silvicultural system is a cycle of activities by which a forest is harvested, regenerated, and tended over time to meet stand or landscape management objectives. Traditional silvicultural systems, first developed in Europe during the 1800s, generally reflect the type of regeneration method employed and the extent of the original forest canopy structure remaining after the initial harvest (e.g., **shelterwood**, seed tree, clearcut, strip cut). The primary management concern of these systems is typically the production of timber. The vast majority of harvesting in British Columbia has used the clearcut silvicultural system. Since the early 1990s, partial cutting or selection systems were used to retain some portion of the original stand structure and to emulate the size and pattern of natural disturbance regimes. In the interior of the province, many of these "retention systems" met a wide variety of ecological and social goals while still allowing for timber

TABLE 7.1 *Site identification criteria for determining operability on Western redcedar – Western hemlock – Salal (01) sites in the CWHvh2*

	Operable sites	**Inoperable sites**
Site series phases[a]	CWHvh2/01a, (01b), more productive sites may be transitional to CWHvh2/04a or 04b	CWHvh2/01c, (01b), sites often transitional to CWHvh2/11 or CWHvh2/13
Indicator plant species[a]	Western redcedar, yellow-cedar, and western hemlock are the dominant tree species; Sitka spruce is uncommon and of low vigour. Forests are open with numerous spike-topped western redcedar. Understorey dominated by Alaskan blueberry, oval-leaved blueberry, and red huckleberry, as well as abundant amounts of salal and false azalea. Lanky moss and step moss are the dominant moss species. Common green sphagnum and skunk cabbage are often present, but not dominant. Absence or scattered presence of Labrador tea, crowberry, lingonberry, sedges, deer-cabbage, Indian hellebore, Pacific reedgrass	Western redcedar, yellow-cedar, western hemlock, and shore pine appear scrubby and are largely limited to the shrub layer (≤ 10 m). Mountain hemlock and shore pine may be more frequent than on "operable" sites. Presence of species indicating poor nutrient availability and wetter conditions, including Labrador tea, crowberry, lingonberry, sedges, deer cabbage, sphagnum mosses (especially common red sphagnum, common brown sphagnum, and fat sphagnum), common scissor-leaf liverwort, Indian hellebore, and Pacific reedgrass. Greater dominance of common green sphagnum, and skunk cabbage. Dominance and high vigour of skunk cabbage indicates CWHvh2/13 (swamp forests); avoid harvesting.
Organic soil depth and composition	< 30 cm Forest floor horizons (LFH) dominate. Usually composed of fine roots, wood, bark, and other plant residues from communities typically associated with "upland" sites. A well-developed H horizon is typical. Peat materials (e.g., residues from sedges and sphagnum mosses or other typically "wetland" species) are absent or minimal.	> 30 cm Peaty organic (O) horizons dominate. These horizons are largely composed of residues from sedges and sphagnum mosses or other plants associated with soil moisture regimes 6–8, with water tables at or near the surface for a significant period during the growing season.
Mineral soil depth	> 20 cm	< 20 cm
Bedrock type	schist gneiss diorite gneissic diorite	granodiorite quartz diorite diorite gneissic diorite
Minimum stand volume	≥ 230 m^3/ha[b]	≤ 230 m^3/ha[b]
Height class	≥ 3	≤ 3
Other operability considerations	Sites include some more productive forest patches (usually site series 04) to increase merchantable volume and balance costs. Area is accessed by minimal disturbance through wet forests (site series 11, 12, 13) or non-forested wetlands (site series 31, 32, 33). Sites dominated by slopes greater than 10%.	No higher-productivity sites (usually site series 04) are present in proximity to site. Access cuts through significant patches of wet forest (site series 11, 12, 13) or non-forested wetland (site series 31, 32, 33). Sites dominated by slopes less than 10%.

a Site series phases and plant common names as per Banner et al. 1993.

b Minimum stand volume represents net volume of conifers and is based on a minimum DBH of 17.5 cm. These volumes are based on results from the Oona River and Port Simpson operational trials. Operable volumes will vary depending on site-specific costs.

harvest. On the coast of British Columbia, however, the species composition, ecological characteristics, and size of the timber, combined with the typically steep terrain, presented significant challenges for the application of partial cutting and retention harvesting techniques. As a result, the use of partial cutting systems has been limited primarily to single- or group-selection cuts done by helicopter, although ground-based or cable systems have been successfully used on the south coast in recent years. On the central and north coast, however, modern experience with partial cutting (as opposed to old selective or high-grading cuts done during the early 1900s) is very limited; harvesting on the lower-productivity cedar–hemlock sites has occurred only recently (e.g., Kumealon Inlet over the past few years). These stands present several new operational concerns that pose challenges for sustainable management. For this reason, we considered several silvicultural systems, both traditional and non-traditional, during the planning of the Port Simpson and Oona River operational trials. While the primary silviculture objective of both trials was to re-establish a productive stand of commercially valuable conifers, another important objective at the Oona River trial was to retain some of the original stand structure and biological complexity.

7.2.1 Block layout Pre-harvest ecosystem mapping of potential harvest units proved an effective tool for the accurate delineation of block boundaries. Air photo interpretation is a critical first step in defining the initial ecosystem boundaries and significantly reduces layout time in the field. Block boundaries should encompass the CWHvh2/01 sites and exclude the much wetter and typically inoperable CWHvh2/11, /12, and /13 site series. If these site series cover greater than 0.1 ha within the block, the areas should be flagged as leave patches and assessed for windthrow potential before final layout. Leave patches within the block will provide structural diversity, wildlife habitat, and a good seed source for natural western redcedar regeneration. To increase the total merchantable volume harvested from any one unit, it may be desirable to include some patches of more productive forest (site series 04 or 05), typically found on steeper slopes adjacent to the CWHvh2/01 sites. Some features that determine operability, such as soil depth and composition and bedrock type, are not discernible from air photos and, therefore, initial block boundaries will require on-site modification. To reduce overall site disturbance and off-site hydrological impacts, planned access routes to and through blocks should avoid areas of wet forest (site series CWHvh2/11, /12, and /13) and non-forested wetlands (site series CWHvh2/31, /32, and /33). Although not yet tried on these specific sites, it may be possible to construct a temporary access road, or a trail across small areas of wet forest or bog, using geotextiles or geosynthetics. These products allow a more even distribution of loads, stabilize and reinforce the soil matrix, and reduce rutting. Avoiding these areas entirely, however, is the preferred option.

After establishing block boundaries and delineating leave patches, plans should be made to promote natural western redcedar regeneration. Retention of western redcedar seed trees throughout the block is highly recommended. Western redcedar seeds are very light (up to 1.3 million seeds per kilogram), but do not travel very far from the parent tree (Burns and Honkala 1990). To increase the likelihood of adequate seed dispersal, we recommend that the distance between a block boundary and an individual seed tree (or group of retained seed trees) be no more than 100 m. Seed trees must withstand long-term exposure to wind, often severe on these sites, and retain some amount of a healthy, live crown. Thus, managers must consider a trade-off in this situation—seed trees with large, healthy crowns that will provide regular seed crops are more susceptible to windthrow and damage than those with thinner, less vigorous crowns (Stathers et al. 1994). This is of particular concern when an isolated tree is left. Small groups of trees provide for better long-term stability and are the preferred option. Large veteran trees, even those with significant amounts of stem rot, can also play an important role as seed trees. These "vets" produce fewer and less frequent seed crops than younger, healthier trees, but are usually more stable and likely to remain standing during severe wind events. The size and location of retained seed trees will ultimately depend on the stand structure present.

7.2.2 Harvesting To maintain or increase tree productivity on the CWHvh2/01 sites, canopy openings are needed to increase sunlight, soil warming, and nutrient availability. Therefore, some form of clearcut with retention harvesting system (e.g., modified diameter limit) is required. To define a workable cutting regime, we highly recommend obtaining additional information on stand structure and composition. We suggest conducting at least two cruise plots per hectare (more if stand composition and structure is highly variable) to collect additional data on diameter class distribution. These data will provide a more complete picture of the species and size distribution present, and allow the setting of suitable diameter limits. Upper and lower diameter limits will depend on size and species distribution and total volume on the site. A significant proportion of the largest diameter western redcedar veterans should be retained as seed trees (see section 7.2.1). In addition, every effort should be made at the time of harvest to retain any advance western redcedar regeneration. On these low-productivity sites, retaining veteran trees should not lower the total harvest volume significantly as these stems typically have high levels of stem rot and provide little, if any merchantable volume. Larger veteran stems located on the richer sites (e.g., CWHvh2/04, /05) harvested in conjunction with these low-productivity stands can be cut. Although specific selection criteria should be determined on a block-by-block basis, the upper limit on the CWHvh2/01 sites typically averages 100–150 cm DBH. Depending on future stand structure goals, merchantable shore pine can either be removed or retained; however, under the Forest Planning and Practices Regulation (Section 46 [2]) shore pine is only considered an "acceptable" crop species, and thus seed tree retention is not recommended. If western hemlock will be a commercial component of the next crop, all mistletoe-infected hemlock stems higher than 2 m must be removed. If the hemlock is not infected with mistletoe, its retention can act as a wind buffer for western redcedar seed trees, enhance visual quality, or improve wildlife habitat values. Hemlock retention will also maintain some canopy interception, and thus reduce the potential for water table rise.

The wet soil conditions typically found on lower-productivity sites, combined with the potentially positive benefits of harvest and site preparation disturbances on second-growth tree productivity, present some significant operational challenges. Some level of site disturbance is beneficial; however, to avoid site degradation and off-site (hydrological) impacts, operators must recognize site- and weather-specific limitations. The CWHvh2/01 site series exhibits variable slope and soil characteristics and these variations result in conditions that respond quite differently to machine traffic. Flat and gently sloping areas with deeper organic soils, and areas with thin organic veneers over bedrock, have greater potential for soil puddling, surface water ponding, and (over the long-term) paludification. This is especially true if operations are not suspended during very wet periods (> 75 mm precipitation in 12 hours). To ensure these sites are not degraded, the current operational shutdown guidelines may require revision. Low-ground-pressure, wide-tracked equipment (e.g., excavators with 32-inch [82 cm] tracks) will minimize the negative effects of machine traffic on these sites, but still provide desirable levels of surface soil disturbance. This equipment is capable of performing multiple functions, such as trail construction, log forwarding, slash piling, and site preparation. Corduroy roads, built of logging slash and dead and down woody material (non-merchantable), should be used for skidding. Using less material, secondary trails can also be constructed and then pulled apart by the machine operator as the area is cleared of logs. This method not only minimizes the site disturbance associated with skid roads, but also aids in slash management. During the harvesting phase of the HyP^3 Project, low-ground-pressure machines (< 6 psi) such as the FMC tracked skidder, proved ideal for transporting logs from the block to the landing or main haul road.

7.2.3 Site preparation treatments Within the CWHvh2, three phases of 01 site series are recognized: 01a – mineral, 01b – lithic, and 01c – peaty (Banner et. al. 1993). The mineral phase has proved the most suitable for mounding or mixing treatments because more opportunities are available to mix surface organic layers with subsurface mineral horizons. On these sites, low, broad mounds are preferred over higher mounds that result in deep pit–mound topography, a condition which favours the establishment of sphagnum mosses and site paludification (see sections 4.3 and 4.4). The lithic phase consists of forest floor (LFH) horizons (sometimes over 40 cm deep) occurring directly over bedrock. The peaty phase is composed of organic soils (generally deeper than 40 cm) derived from sphagnum moss. On sites of either phase, mounding of pure organic material is not expected to improve productivity except, perhaps, through some marginal improvement of surface soil aeration. Excessive machine traffic and site preparation on these non-mineral phases will likely lead to soil puddling, a decrease in the number of plantable spots, and a decline in long-term site productivity. The best strategy on the lithic and peaty phases is to use naturally elevated microsites when choosing plantable spots (e.g., beside stumps). These sites will only be subjected to the surface disturbance created by harvesting activities, and these activities should be curtailed during very wet periods. Raking treatments to reduce the accumulated organic matter and slash can be applied to all phases of the CWHvh2/01 site series as well as 04 sites. On sites series CWHvh2/11 (occurring mainly on peaty soils), initial treatment results indicate that harvesting should be avoided wherever possible (see section 7.2.1).

Our operational trials show that machine operators must receive a basic level of training to recognize the soil conditions appropriate for applying site treatments. From an operational perspective (based on feedback from the machine operators), harvesting and hoe-chucking activities should be combined with the site preparation activities to minimize the number of entries into the block. After assessing soil conditions by visual indicators and by test-probing with the excavator bucket or rake, operators can apply the appropriate raking or mounding treatments as they retreat from that area of the block.

7.2.4 Planting Although harvesting and mechanically treating the CWHvh2/01 sites should encourage natural regeneration of western redcedar, planting should be carried out within 1 year of completing the site treatments (i.e., allow mixed and mounded spots to settle over a winter before planting). To achieve the optimum planting density, seedlings should be planted on both the naturally raised microsites and the artificially created mounds. Western redcedar is the most ecologically and economically suitable species for these sites and should make up the majority of planted stems. Experience with planting yellow-cedar on these sites is limited; however, it is a naturally occurring species and is considered acceptable as a minor component of the stand (e.g., up to 20%). Although western hemlock is currently listed as a primary species on these sites (Banner et al. 1993), planting is not recommended for the following reasons:

- natural regeneration will occur on all sites;
- the cost of planting is not justified as the species is of less economic value than western redcedar; and
- hemlock dwarf mistletoe (*Arceuthobium tsugense*) can be a significant problem on these sites, thereby reducing overall yield and value.

Browsing of planted western redcedar by coastal black-tailed deer (*Odocoileus hemionus*) is often very heavy on these sites and seedling protection is therefore considered mandatory. Although various types of seedling protectors are available, the type selected should be at least 1.2 m tall. Manual removal of tree protectors significantly increases total establishment costs, particularly on remote, difficult to access sites. We, therefore, recommend protectors that are designed to photodegrade in 5–8 years (depending on site location and growth rates). Since photodegradation rates are quite inconsistent, the costs of follow-up site inspections and maintenance must be included. Stake size and quality are also critically important as a broken stake will result in the loss of the seedling. A 2.5 × 2.5 × 150 cm knot-free wood stake, preferably western redcedar, that is driven into the ground a minimum of 30 cm is recommended. Because high winds and snow press often cause the most damage to seedling protectors, two stakes per protector may be required (Henigman and Martinz 2001). Some protector designs require only a single stake, but may need some sort of additional pin to prevent the structure from shifting. Protection of seedlings should be done concurrently with planting.

As part of our efforts to protect planted western redcedar seedlings from deer browsing, we recently initiated a research trial to determine the effectiveness and practicality of using seedlings derived from rooted cuttings taken from unbrowsed, advance western redcedar regeneration. Research shows that deer browsing is sensitive to the levels of monoterpenes in the foliage (Vourc'h et al. 2001, 2002). The unbrowsed advance regeneration may contain higher levels of monoterpenes, and cuttings taken from this root stock could retain this chemical defence. In addition, we are examining numerous nursery fertilizer regimes to determine whether these affect a seedling's palatability to deer. Some combination of higher levels of natural chemical defence and altered foliage palatability may eventually reduce the need to protect seedlings from deer browse. Seedlings for these trials were planted at Oona River in the spring of 2004.

7.3 Future Research Direction

Through the HyP^3 Project, we have learned a great deal about the ecology, hydrology, silviculture, and management of hypermaritime forests and related nonforested ecosystems. This knowledge has supplemented our previous experience gained from over 25 years of ecological research in coastal British Columbia. The combination of pure science, involving co-operation among specialists from related fields, and practical operational trials has resulted in some initial management guidelines with a solid ecological foundation. Nevertheless, we have just scratched the surface in the study of the long-term development of these cedar–hemlock forests following disturbance. Our stem analysis work in old-growth forests provided some clues about their development that we have compared with initial growth rates in second-growth stands. We still face uncertainties, however, about projecting these growth rates into the future, and these will only be lessened with continuing research.

Some of the HyP^3 scientists have recently initiated an ecosystem recovery project on the north coast of British Columbia that involves detailed ecological sampling in older second-growth stands. While searching for study stands that had originated from forest harvesting over the last century, several locations were discovered where 150–250-year-old, second-growth cedar stands had developed after fire, probably Aboriginal burning. Many of these stands represent second-growth CWHvh2/01 sites and will provide valuable data on forest development following disturbance. This information, as well as observations (by the authors) of a few recently regenerated cedar-dominated stands on slash-burnt cutblocks, suggests that fire may be a potential management tool on CWHvh2/01 sites and thus needs further research.

With the completed HyP^3 research as a foundation, monitoring of our existing operational trials must continue and new trials established throughout the coast. Similar forest ecosystems to those studied on the mainland coast occur on Haida Gwaii/the Queen Charlotte Islands, and thus opportunities exist there for the application of results and the establishment of operational trials. Our operational trials on the mainland coast are all located on richer metamorphic bedrock. Although monitoring of some previously established second-growth stands on the poorer granodiorites was also part of the HyP^3 studies, additional trials on this widespread bedrock must be established. This is necessary to further test our initial conclusions that, compared with the meta- morphic areas, these sites have lower second-growth productivity and operational potential (though still higher than the old-growth stands indicate). Future operational trials should include a hydrological component to monitor soil and watershed hydrology 1–2 years before forest harvesting and for at least 2 years after harvest. This was the intended approach at the Smith Island study site, where extensive hydrology data were collected; however, logistics, economics, and visual constraints prevented harvesting on this site. While we learned a great deal about the baseline hydrology of hypermaritime watersheds, which allowed us to speculate informatively about the hydrological effects of harvesting, we still lack actual before and after scenarios. The HyP^3 studies now provide a wealth of baseline knowledge and data on which to build an effective pre- and post-harvest hydrological monitoring program within future operational trial areas.

Many opportunities also exist for co-operative research with our counterparts in southeast Alaska. Some joint field trips have already permitted us to observe and discuss common forest ecology and management concerns. Four high-priority issues have emerged as having the greatest potential for co-operative research efforts (D. D'Amore and P. Hennon, U.S. Department of Agriculture Forest Service, Juneau, Alaska, pers. comm., November, 2004):

1. Developing a common framework in which to apply ecosystem classification and mapping in coastal British Columbia and southeast Alaska.
2. Using age structure analysis to better quantify disturbance histories across various hypermaritime stand and site types; in particular, to better quantify the role that wind has played in stand (and soil) development.
3. Quantifying second-growth productivity in wet, lower-productivity forest types and better defining limits of operability along the upland forest–bog forest continuum.

4. Better defining the problem of yellow-cedar decline (i.e., its extent, causes, implications, and potential solutions).

Further development and refinement of guidelines for these and other shared forest ecology and management issues would be significantly enhanced by cross-border co-operation in pure research and operational trials.

Because operational trials are cost-effective and more likely to provide immediate, practical results, they are becoming the favoured research approach. We should not, however, ignore the need for continued baseline research on ecosystem function. Future research in the hypermaritime upland forest–blanket bog complex should also include components that continue to examine the soil and vegetation ecology, nutrient cycling, and hydrology of this fascinating landscape.

The research results and operational recommendations of the HyP^3 Project, together with future research and operational trial initiatives of this and related projects, will hopefully contribute to effective ecosystem- and science-based management in coastal areas of British Columbia.

APPENDIX 1 HyP^3 Project-related Extension Notes

B.C. Ministry of Forests Research extension notes are available at:
www.for.gov.bc.ca/rni/Research/Extension_notes/ Extension_Notes.htm

University of British Columbia Extension Series are available from the authors of this report.

Note #	Title
B.C. Ministry of Forests Research Extension Notes	
38	Pattern, process, and productivity in hypermaritime forests: The HyP^3 Project
39	Basin hydrology and canopy interception in hypermaritime forests: Issues and approach
44	Excavator mounding to enhance productivity in hypermaritime forests: Preliminary results
45	Effects of soil mixing on foliar nutrient content of shore pine in hypermaritime forests of northern British Columbia: Preliminary results
48	The Oona River operational research trial
49	Canopy interception in a hypermaritime forest on the north coast of British Columbia
50	Moss growth, production, and paludification in the hypermaritime north coast of British Columbia
51	Surface water discharge and groundwater storage patterns in a hypermaritime bog near Prince Rupert, B.C.
52	The blanket bog–upland forest complex of north coastal British Columbia: Succession, disturbance, and implications for management
54	Soil biogeochemical dynamics in hypermaritime ecosystems of north coastal British Columbia
University of British Columbia Extension Series (*Scientia Silvica*)	
42	Regeneration, growth, and productivity of trees within gaps of old-growth forests on the outer coast (CWHvh2) of British Columbia

For additional information on the HyP^3 Project, please refer to the Web site at:
www.for.gov.bc.ca/rni/Research/HyP3/hyp3-pg1.htm

GLOSSARY[8]

Aerobic – occurring in the presence of oxygen as applied to chemical and biochemical processes; opposite of anaerobic.

Anaerobic – occurring in the absence of oxygen as applied to chemical and biochemical processes.

Basal area – the cross-sectional area at breast height (1.3 m) of all the stems of interest in a stand over a unit of land area; expressed as m^2/ha.

Baseflow – the contribution that groundwater makes in sustaining water yields in a watercourse during periods of no rainfall or snowmelt.

Biogeoclimatic Ecosystem Classification (BEC) – a hierarchical ecosystem classification system applied in British Columbia that describes variation in climate, vegetation, and site conditions.

Brunisol – a soil order containing soils that have sufficient development to exclude them from the Regosolic order; has a B horizon showing some soil genesis.

Bulk density – the mass of dry soil per unit volume. Also used in this report as moss bulk density: g/cm of linear growth per square metre.

Climax vegetation – stable, self-perpetuating vegetation that represents the final stage of succession.

Colluvium – unconsolidated material moved by gravity, often occurring at middle or lower slope positions.

First-order stream – an unforked or unbranched stream. Two first-order streams flow together to form a second-order stream, two second-order streams combine to make a third-order stream, etc.

Folisol – a soil order containing soils composed of upland organic materials, generally of forest origin, that are greater than 40 cm thick, or at least 10 cm thick if over bedrock or fragmental materials.

Gleysol – a soil order containing soils that are saturated with water and under reducing conditions either continuously or for a significant period of the year.

Hardpan – horizons or layers in soils that are strongly compacted, hardened, cemented, or very high in clay content.

Hummock – a small, mounded rise of organic matter and vegetation on a level surface.

Hydraulic conductivity – a coefficient of proportionality describing the rate at which water can move through a permeable medium.

Hydraulic gradient – the gradient or slope of a water table.

Hydrograph separation – a technique that uses the composition of water from different sources and in the receiving area to calculate the proportion of the total water coming from each contributing source.

Lag time – has various definitions; used here to measure the difference between the start of a rainfall event and a measurable response in a stream.

Lawn – a level area in a peatland with an elevation between that of a hummock and a hollow.

Macropore – a preferential flow channel whose effect is most pronounced on infiltration.

Minerotrophic – receiving nutrients from groundwater containing dissolved minerals.

[8] Based in part on Cauhoue et al. 1996

Net primary production (NPP) – the gross primary production of plants minus the biomass used in respiration by primary producers.

Orographic precipitation – precipitation that results from the lifting of moist air over an orographic barrier such as a mountain range.

Overland flow – water that travels over the ground surface to a point of concentration where turbulent flow occurs.

Paludification – process of bog expansion caused by a gradual rise in water table, or development of a perched water table as peat accumulation impedes drainage. Mineral soils are transformed into organic soils as bog vegetation expands.

Peak flow – the maximum instantaneous discharge of a stream or river at a given location. It usually occurs at or near the time of maximum flood.

Predictive ecosystem mapping (PEM) – a method of predicting ecosystem occurrence on the landscape using available spatial data and knowledge of ecological and landscape relationships. This information is used to automate the computer generation of ecological map units.

Perched groundwater – a water table formed by the perching of water on a relatively impermeable layer at some depth within the soil. The soil within or below the impermeable layer is not saturated with water.

Piezometer – an instrument for measuring the pressure head of liquids.

Podzol – a soil order containing soils in which the dominant accumulation product in the B horizon is amorphous material composed mainly of Fe, Al, and (or) organic carbon.

Preferential flow – water flow through channels in the soil and not the soil matrix.

Quick flows – water that is immediately released from a watershed (see baseflow).

Redox – sometimes reactants gain and lose electrons, as in oxidation–reduction, or redox, reactions. In an oxidation–reduction reaction, one reactant is oxidized (loses one or more electrons) and the other reactant is reduced (gains one or more electrons).

Regosol – a soil order containing weakly developed soils in which there is not a recognizable B horizon at least 5 cm thick.

Retranslocation – the movement of nutrients between older and newer foliage within a plant.

Saprolite – bedrock decomposed *in situ.*

Shelterwood – a silvicultural system that involves the retention of a small number of widely dispersed trees for seed production in order to regenerate a new age class in an exposed microenvironment.

Site index – a species-specific measure of forest productivity expressed in terms of height of trees at a specified age (usually 50 years at breast height in British Columbia).

Site Index – Biogeoclimatic Ecosystem Classification (SIBEC) – site index measurements tied to the BEC system.

Site series – sites capable of producing the same mature or climax plant communities within a biogeoclimatic subzone or variant.

Soil pipe – subsurface channels parallel to the slope that are sufficient in length to influence the flow processes at the hillslope scale.

Terrain resource inventory mapping (TRIM) – the provincial program to prepare computerized base maps for British Columbia at the 1:20 000, 1:250 000, and 1:2 000 000 scales.

Terrestrial ecosystem mapping (TEM) – the stratification of the landscape into map units according to a combination of ecological features, primarily climate, physiography, surficial material, bedrock geology, soil, and vegetation.

Time Domain Reflectrometry (TDR) – a method of measuring soil water content using electromagnetic pulses.

Water table – the upper surface of a sub-terrestrial water saturation zone; the elevation at which the pressure in the water is zero with respect to atmospheric pressure.

Zonal site – a site that is intermediate in soil moisture and nutrient status within a biogeoclimatic unit. The vegetation on a zonal site thus reflects the overriding influence of regional climate.

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